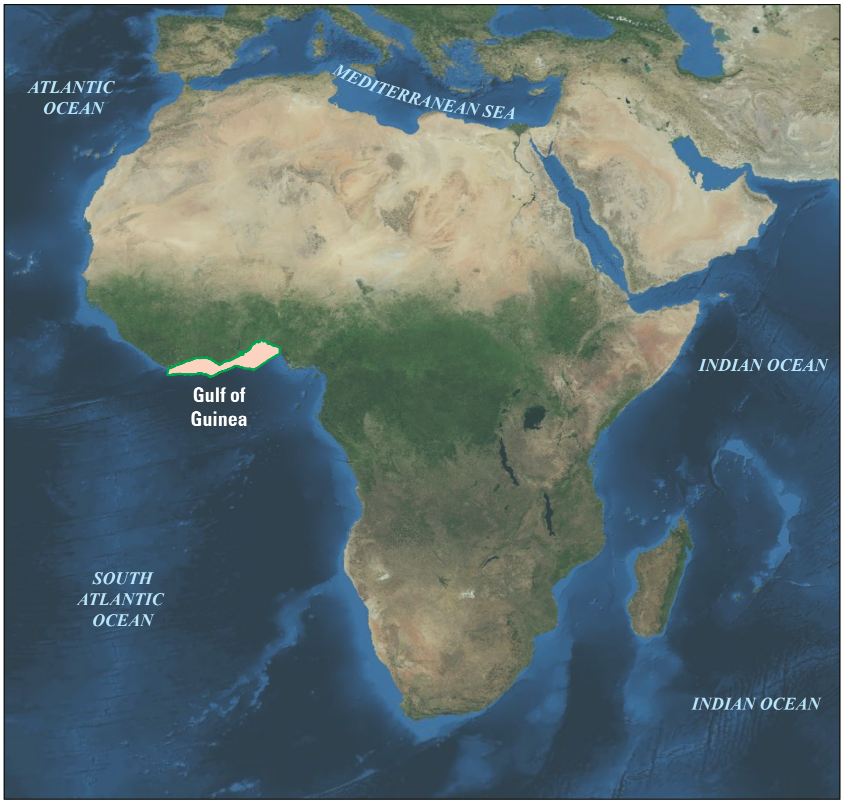
Assessment of Undiscovered Oil and Gas Resources of the Gulf of Guinea Province, West Africa

By Michael E. Brownfield



Click here to return to
Volume Title Page

Chapter 4 of
Geologic Assessment of Undiscovered Hydrocarbon Resources of Sub-Saharan Africa
Compiled by Michael E. Brownfield

Digital Data Series 69–GG

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Director

U.S. Geological Survey, Reston, Virginia: 2016

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod/.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Although this information product, for the most part, is in the public domain, it also may contain copyrighted materials as noted in the text. Permission to reproduce copyrighted items must be secured from the copyright owner.

Suggested citation:
Brownfield, M.E., 2016, Assessment of undiscovered oil and gas resources of the Gulf of Guinea Province, west Africa, *in* Brownfield, M.E., compiler, Geologic assessment of undiscovered hydrocarbon resources of Sub-Saharan Africa: U.S. Geological Survey Digital Data Series 69–GG, chap. 4, 27 p., http://dx.doi.org/10.3133/ds69GG.

ISSN 2327-638X (online)

Contents

Abstract 1
Introduction 1
Tectonic History of the Gulf of Guinea Province, West Africa 4
Geology 11
    Pretransform Stage 11
    Syntransform Stage 11
    Posttransform Stage 16
Total Petroleum Systems and Petroleum Occurrence in Gulf of Guinea Province, West Africa 18
    Source Rocks 19
    Generation and Migration 20
    Reservoirs, Traps, and Seals 21
Exploration 24
Geologic Model 24
Resource Summary 25
For Additional Information 26
Acknowledgments 26
References 26

Figures

1. Map showing location of Gulf of Guinea Province, west Africa 2
2. Map showing location of Coastal Plain and Offshore Assessment Unit, Gulf of Guinea Province, west Africa 3
3. Map showing major features of the Gulf of Guinea Province, west Africa 5
4. Map showing generalized geology of the Gulf of Guinea area 6
5. Paleotectonic maps showing the evolution continental margins of west Africa and South America 7
6. Maps showing schematic Cretaceous stages in Mesozoic breakup of Africa and South America and the tectonic evolution of the Equatorial Atlantic 8
7. Sketch map showing major fracture zones, sediment thickness, and oceanic-continental boundary of Gulf of Guinea Province 9
8. Generalized stratigraphic columns within Gulf of Guinea Province 10
9. Generalized composite stratigraphic column of offshore and onshore parts of Saltpond and Tano Basins, Gulf of Guinea Province 12
10. Generalized stratigraphic column of drill hole Dzita-1, Keta Basin, eastern Ghana 13
11. Map showing paleogeographic reconstruction of the Silurian Period 14
12. Generalized stratigraphic column of offshore part of Benin Basin, Gulf of Guinea Province 15
13. Generalized stratigraphic column for rocks in the central and western parts of Ivory Coast Basin, Gulf of Guinea Province 17

14. Events chart for the Lower Paleozoic Petroleum System (717301) in Saltpond, Keta, and Tano Basins, Gulf of Guinea Province 18
15. Events chart for the Lower Cretaceous Total Petroleum System (717301) in the Ivory Coast, Tano, Keta, and Benin Basins, Gulf of Guinea Province....19
16. Events chart for the Cretaceous Composite Petroleum System (717301) and the Coastal Plain and Offshore Assessment Unit in the Ivory Coast Basin, Gulf of Guinea Province....20
17. Modeled burial-history curves and vitrinite reflectance and temperature diagrams of well Dzita-1, Keta Basin, Ghana 21
18. Generalized geoseismic cross section of offshore part of Benin Basin, Gulf of Guinea Province....22
19. Schematic cross section across the Belier and Espoir fields in Ivory Coast Basin, Gulf of Guinea Province 23
20. Schematic cross section showing common trap types and oil- and gas-field analogs in Gulf of Guinea Province....25

Table

1. Gulf of Guinea Province and Coastal Plain and Offshore Assessment Unit results for undiscovered, technically recoverable oil, gas, and natural gas liquids 26

Assessment of Undiscovered Oil and Gas Resources of the Gulf of Guinea Province, West Africa

By Michael E. Brownfield

Abstract

The main objective of the U.S. Geological Survey's National and Global Petroleum Assessment Project is to assess the potential for undiscovered, technically recoverable oil and natural gas resources of the United States and the world. As part of this project, in 2011 the USGS completed an assessment of the Gulf of Guinea Province, an area of about 236,670 square kilometers. This assessment was based on data from oil and gas exploration wells, producing fields, and published geologic reports. The Gulf of Guinea Province as defined by the U.S. Geological Survey includes the coastal and offshore areas of Côte d'Ivoire, Ghana, Togo, and Benin, and the western part of the coast of Nigeria. The province contains the Ivory Coast, Tano, Central, Saltpond, Keta, and Benin Basins and the Dahomey Embayment.

The Cretaceous Composite Total Petroleum System and its associated assessment unit, the Coastal Plain and Offshore Assessment Unit, were assessed in this study. The Gulf of Guinea Province is different in two important ways compared to the passive-margin basins south of the Niger Delta: transform-fault tectonics strongly influenced it, and evaporites and associated salt deformation are absent. The province also lacks large, long-lived deltaic systems that typically result in rapid source-rock burial and abundant high-quality hydrocarbon reservoir systems.

Hydrocarbons were generated from Early to Late Cretaceous marine source rocks. The primary source rocks are Turonian in age and contain Type II kerogen. Generation possibly started in the early Tertiary and continues to the present. Hydrocarbons migrated into Cretaceous sandstone reservoirs, including syntransform and posttransform ponded turbidites, turbidite channels, and slope fans between major fracture zones and minor limestone units. Hydrocarbons migrated from adjacent source rocks or upward along faults from deeper sources. The traps include pretransform traps related to fault blocks, syntransform structural and stratigraphic traps, and posttransform stratigraphic traps. Reservoir seals are mainly marine shale, shale-filled channels, and minor fault-related seals.

The U.S. Geological Survey assessed the potential for undiscovered conventional oil and gas resources in the Gulf of Guinea Province and estimated a mean of 4,071 million barrels of conventional undiscovered oil, 34,461 billion cubic feet of gas, and 1,145 million barrels of natural gas liquids. Most of the hydrocarbon potential is postulated to be in the offshore, deeper waters of the province. Gas resources may be large in areas where the zone of hydrocarbon generation is relatively shallow.

Introduction

The main objective of the U.S. Geological Survey's (USGS) National and Global Petroleum Assessment Project is to assess the potential for undiscovered, technically recoverable oil and natural gas resources of the United States and the world (U.S. Geological Survey World Conventional Resources Assessment Team, 2012). As part of this project, in 2011 the USGS completed an assessment of the Gulf of Guinea Province (fig. 1), an area of about 236,668 square kilometers (km^2) that covers parts of Côte d'Ivoire, Ghana, Togo, and Benin, and the western part of the coast of Nigeria from the Liberia border east to the west edge of the Niger Delta. This assessment was based on data from oil and gas exploration wells, producing fields (IHS Energy, 2008), and published geologic reports.

In USGS World Assessment 2000 (U.S. Geological Survey World Energy Assessment Team, 2000), the assessment estimated mean undiscovered volumes of 1,004 million barrels of oil (MMBO), 10,071 billion cubic feet of gas (BCFG), and 282 million barrels of natural gas liquids for the Gulf of Guinea Province (Brownfield and Charpentier, 2006a). The Gulf of Guinea Province was reassessed for this report because of increased energy exploration activity and interest in its future oil and gas resource potential. The assessment was geology based and used the total petroleum system concept. The geologic elements of a total petroleum system consist of hydrocarbon source rocks (source rock maturation and hydrocarbon generation and migration), reservoir rocks (quality and distribution), and traps (for hydrocarbon accumulation). Using these geologic criteria, the USGS defined the Cretaceous Composite Total Petroleum System (TPS) with one assessment unit, the Coastal Plain and Offshore Assessment Unit (AU) (fig. 2), encompassing about 236,668 km^2, that includes the offshore parts of the province to a water depth of 4,000 meters (m).

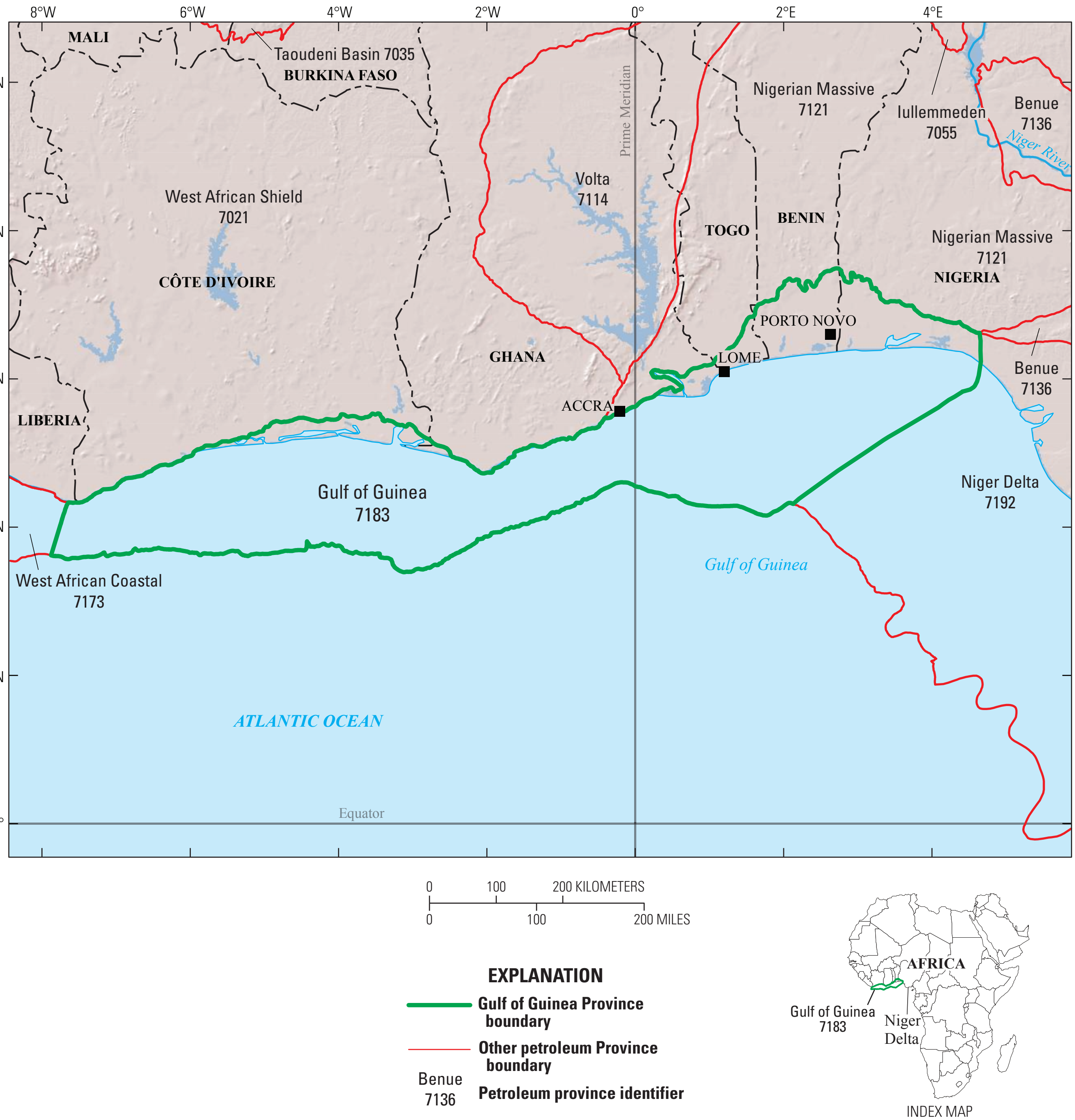


Figure 1. Location of the Gulf of Guinea Province, west Africa.

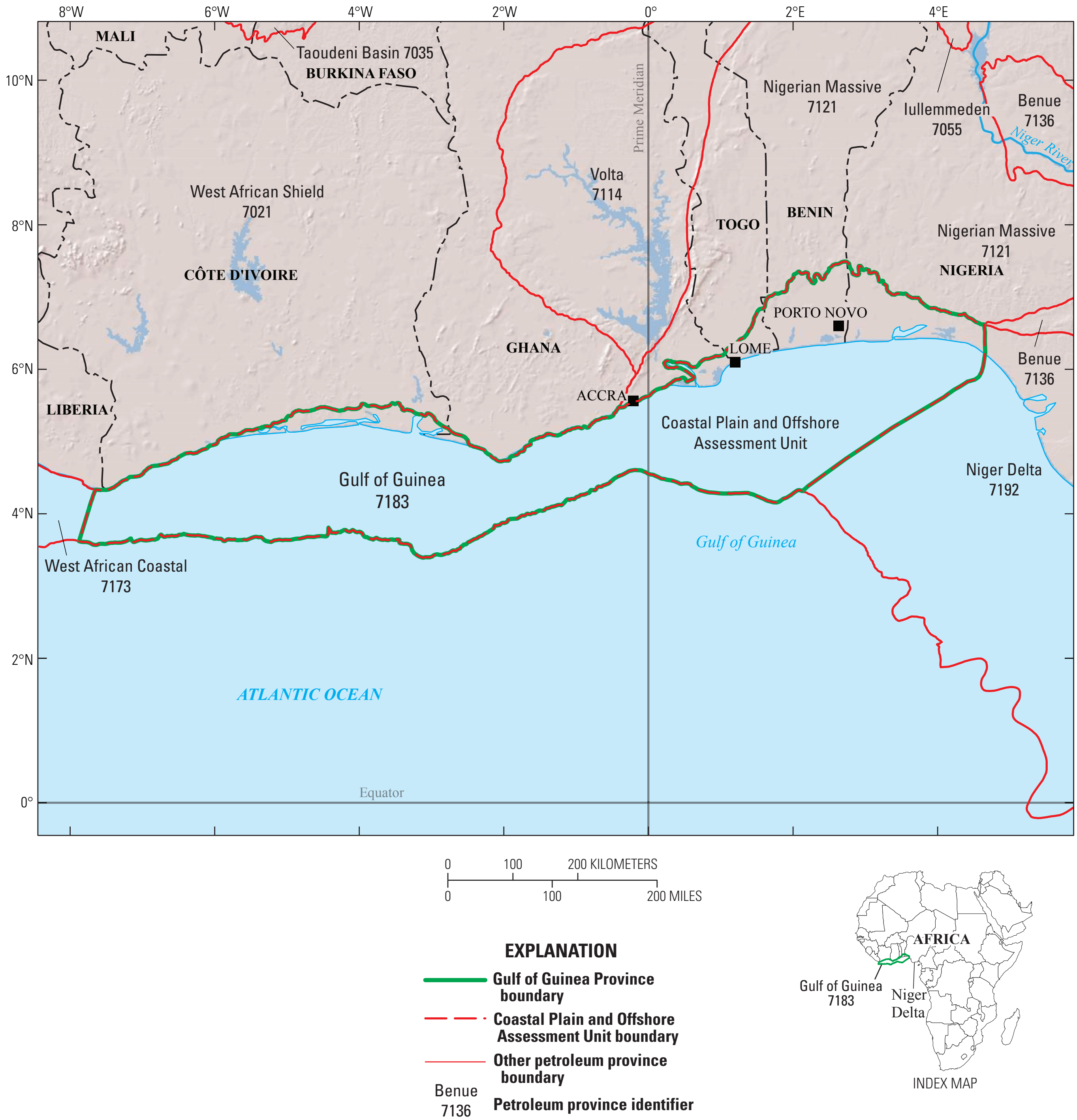


Figure 2. Location of the Coastal Plain and Offshore Assessment Unit, Gulf of Guinea Province, west Africa.

The Gulf of Guinea Province includes the Ivory Coast, Tano, Saltpond, Central, Keta, and Benin Basins in the northwestern part of the Gulf of Guinea (figs. 3, 4). These basins are grouped together as one province for assessment purposes because they share common structural and stratigraphic characteristics, in that they are wrench-faulted basins (Clifford, 1986) and contain rocks ranging in age from Ordovician to Holocene (Kjemperud and others, 1992). The eastern boundary of the province is the Niger Delta Province (Klett and others, 1997), and the western boundary is the West African Coastal Province (fig. 4).

Tectonic History of the Gulf of Guinea Province, West Africa

The Gulf of Guinea formed at the culmination of Late Jurassic to Early Cretaceous tectonism that was characterized by both block and transform faulting; this faulting was superimposed on an extensive Paleozoic basin during breakup of the African, North American, and South American paleocontinents (figs. 5, 6). Thus, the province has undergone a complex history which is divided into pretransform (late Proterozoic to Late Jurassic), syntransform (Late Jurassic to Early Cretaceous), and posttransform (Late Cretaceous to Holocene) stages of basin development. These three stages are also referred to as the pre-rift (or intracratonic), syn-rift (or rift), and post-rift (or drift) stages (Brownfield and Charpentier, 2006b). The structural basins within the province are aligned generally east-west, with boundaries delimited by an east-west transform-fault system (fig. 3) and north-south structural arches.

The initial phase of the post-Hercynian opening of the North Atlantic and the splitting of North America from Eurasia and Africa began during Late Permian–Early Triassic time (Lehner and De Ritter, 1977; Ziegler, 1988; Lambiase, 1989). The final breakup of Africa and South America began in the Late Jurassic in the southernmost part of the south Atlantic and progressed northward during Neocomian time (Binks and Fairhead, 1992; Guiraud and Maurin, 1992). The area now occupied by the Gulf of Guinea opened last and formed a continuous-anoxic seaway in the late Albian to Turonian (Tissot and others, 1980). A continuous-oxic Atlantic Ocean existed by the end of the Santonian (Blarez and Mascle, 1988). Aptian evaporites and clastic units in the West-Central Coastal Province to the south (fig. 4) provide evidence of rift-basin sedimentation during the Early Cretaceous that was associated with the breakup of the Africa and South America paleocontinents.

The early tectonic history of the Gulf of Guinea Province differs from that of the West-Central Coastal Province (fig. 4) or the “Aptian salt basin” (Blarez and Mascle, 1988; Mascle and others, 1988; MacGregor and others, 2003; Brownfield and Charpentier, 2006a). In the evolution of the “Aptian salt basin,” extensional or block faulting dominated the rifting stage and formed grabens that filled with lacustrine and fluvial sediment. This stage was followed by deposition of regional evaporites and subsequent halokinesis (McHargue, 1990; Teisserenc and Villemin, 1990). The Gulf of Guinea Province shows two important geological differences compared to the passive-margin basins south of the Niger Delta: the influence of transform tectonics, and the absence of evaporites and halokinesis. Middle Jurassic volcanic rocks occur in the Gulf of Guinea Province, indicating that tectonism started no later than the Middle Jurassic (Dumestre, 1985; Kjemperud and others, 1992).

Transform faulting was initiated between the African and South American continental plates in Early Cretaceous time (Hauterivian, fig. 6*A*). The thick continental crust of the African and South American platform started to fragment and formed divergent basins or pull-apart grabens separated by transform faults (Blarez and Mascle, 1988) in early Albian time (fig. 6*B*). Thick continental clastic sediments, containing fluvial and possibly lacustrine facies, were deposited in the divergent basins. In the Dahomey Embayment (figs. 3, 4), chemical and geologic characteristics of source-rock samples are similar to those of Lower Cretaceous lacustrine source rocks in the Congo Basin (Haack and others, 2000). Such rocks may also be present in the Benue Trough (fig. 6) and in the Keta and Ivory Coast Basins (fig. 3). Transform tectonism was active between the African and South American plates until middle to late Albian time, when the first oceanic crust was formed (fig. 6*C*) and the last connection between the two continents was breached (Blarez and Mascle, 1988). The end of syntransform tectonism and sedimentation in the Gulf of Guinea Province coincides with this phase. A major Albian to lower Cenomanian unconformity was a direct consequence of the final separation of the continental margins (Blarez and Mascle, 1988; Chierici, 1996; MacGregor and others, 2003). By Santonian time (fig. 6*D*), continued crustal extension resulted in the formation of widespread oceanic crust, and clastic deposition increased in the province’s marginal basins and offshore platform. Thermal subsidence resulted in several Late Cretaceous and Tertiary unconformities.

The Gulf of Guinea Province is divided structurally by three major transform fault or fracture zones (figs. 3, 7): the St. Paul, the Romanche, and the Chain. The St. Paul fracture zone lies along the northwestern boundary, the Romanche fracture zone separates the Ivory Coast and the Central and Saltpond Basins from the Keta Basin, and the Chain fracture zone lies along the province’s eastern boundary. Sedimentary fill within the Ivory Coast Basin is more than 6,000 m thick (fig. 7) north of the Romanche fault zone, which acted as a dam to prevent the transport of sediment to the south.

The three-stage tectonic evolution in the Gulf of Guinea Province allows the stratigraphic section to be divided into three primary sequences (fig. 8). Precambrian to Triassic intracratonic rocks and Jurassic to Lower Cretaceous continental to marginal marine rocks represent the pretransform stage, Lower Cretaceous to latest Albian rocks represent the syntransform stage, and Cenomanian to Holocene rocks represent the posttransform stage.

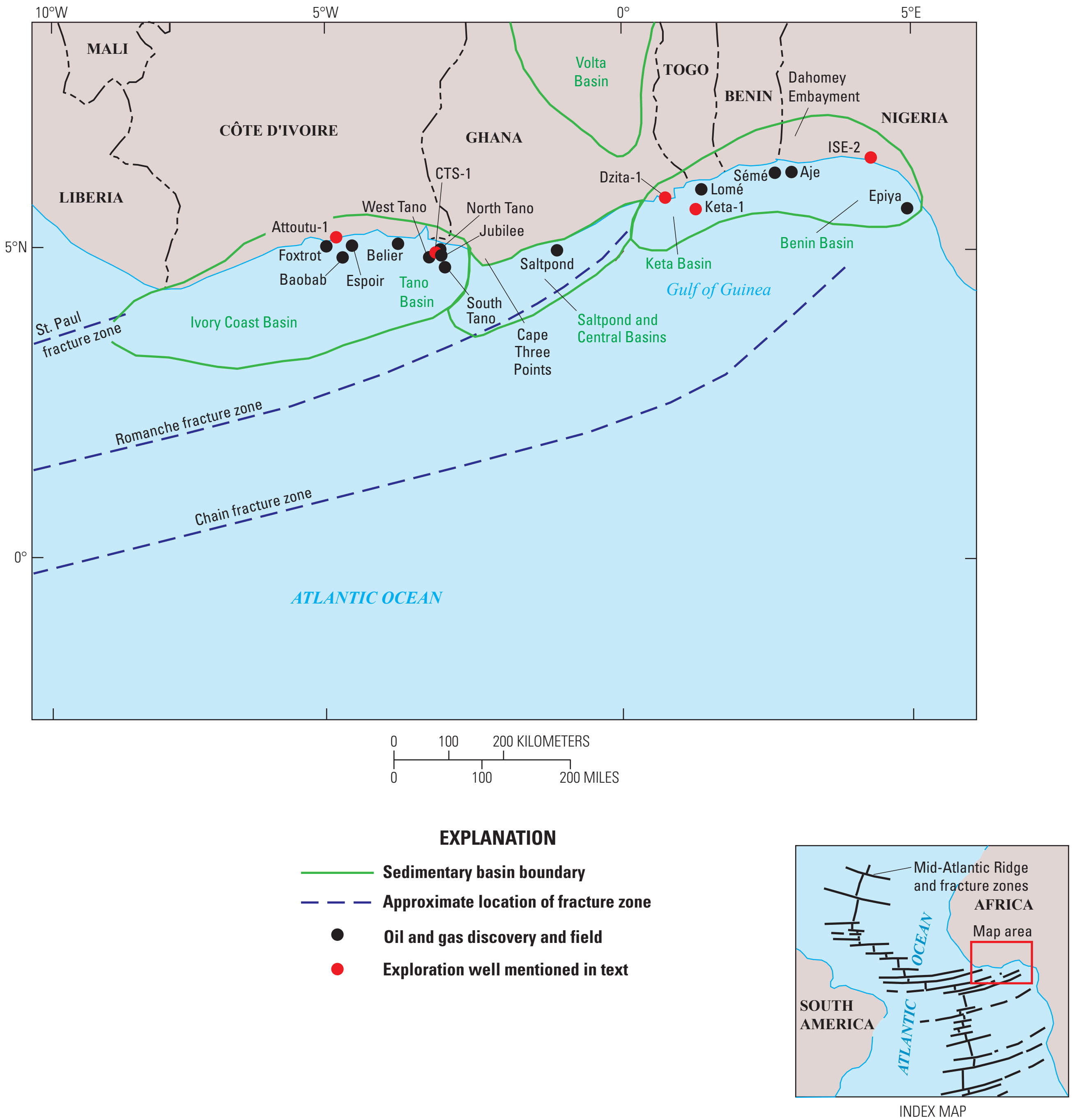


Figure 3. Major features of the Gulf of Guinea Province, west Africa: Benin, Central, Ivory Coast, Keta, Saltpond, Tano, and Volta Basins, Cape Three Points, major fracture zones, and approximate locations of exploration wells and oil and gas discoveries and fields mentioned in the text. Mid-Atlantic Ridge and fracture zones shown on the index map. Modified from Kjemperud and others (1992).

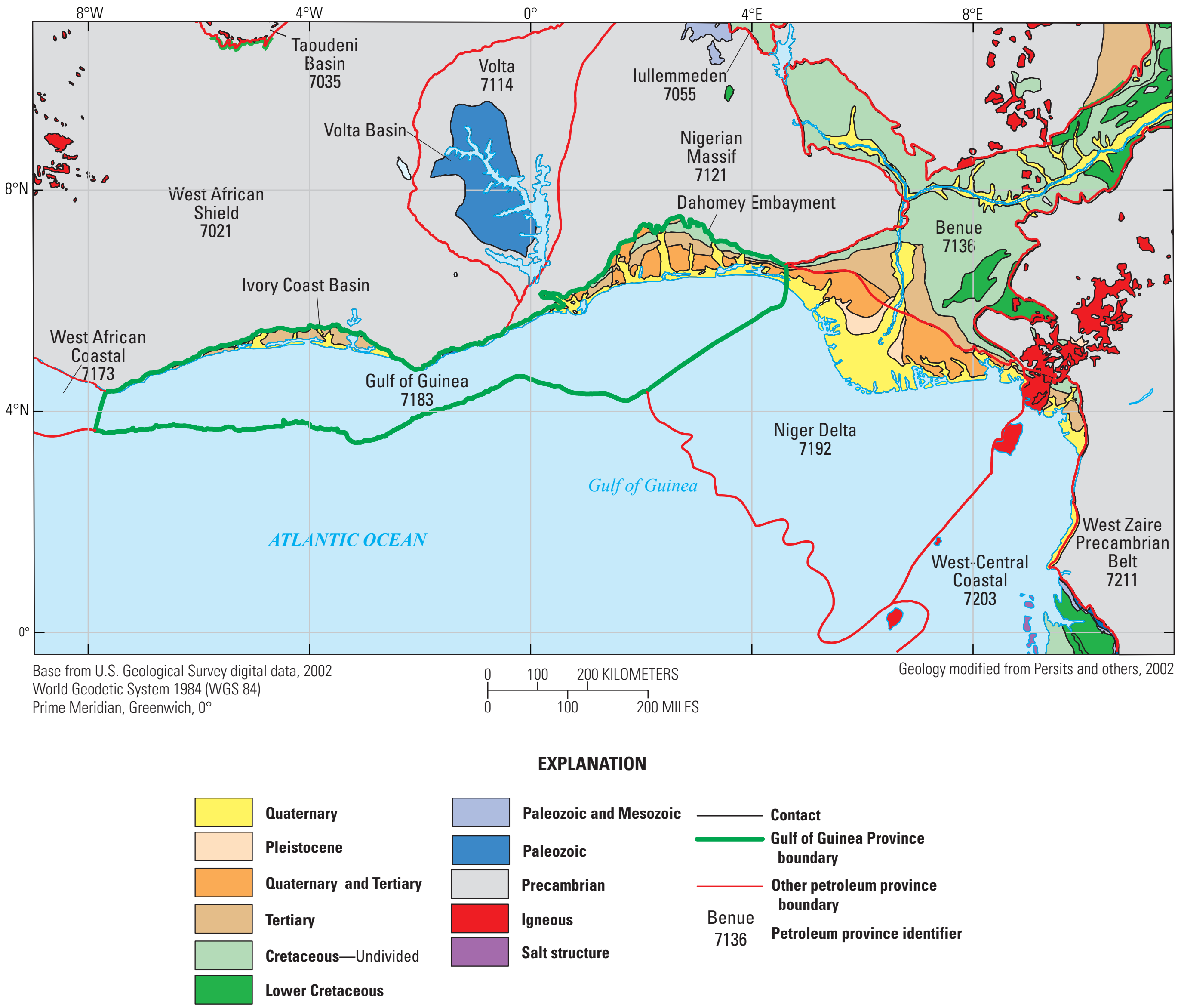


Figure 4. Generalized geology of the Gulf of Guinea area showing 11 U.S. Geological Survey petroleum provinces, the Dahomey Embayment, and the Ivory Coast and Volta Basins. Modified from Persits and others (2002).

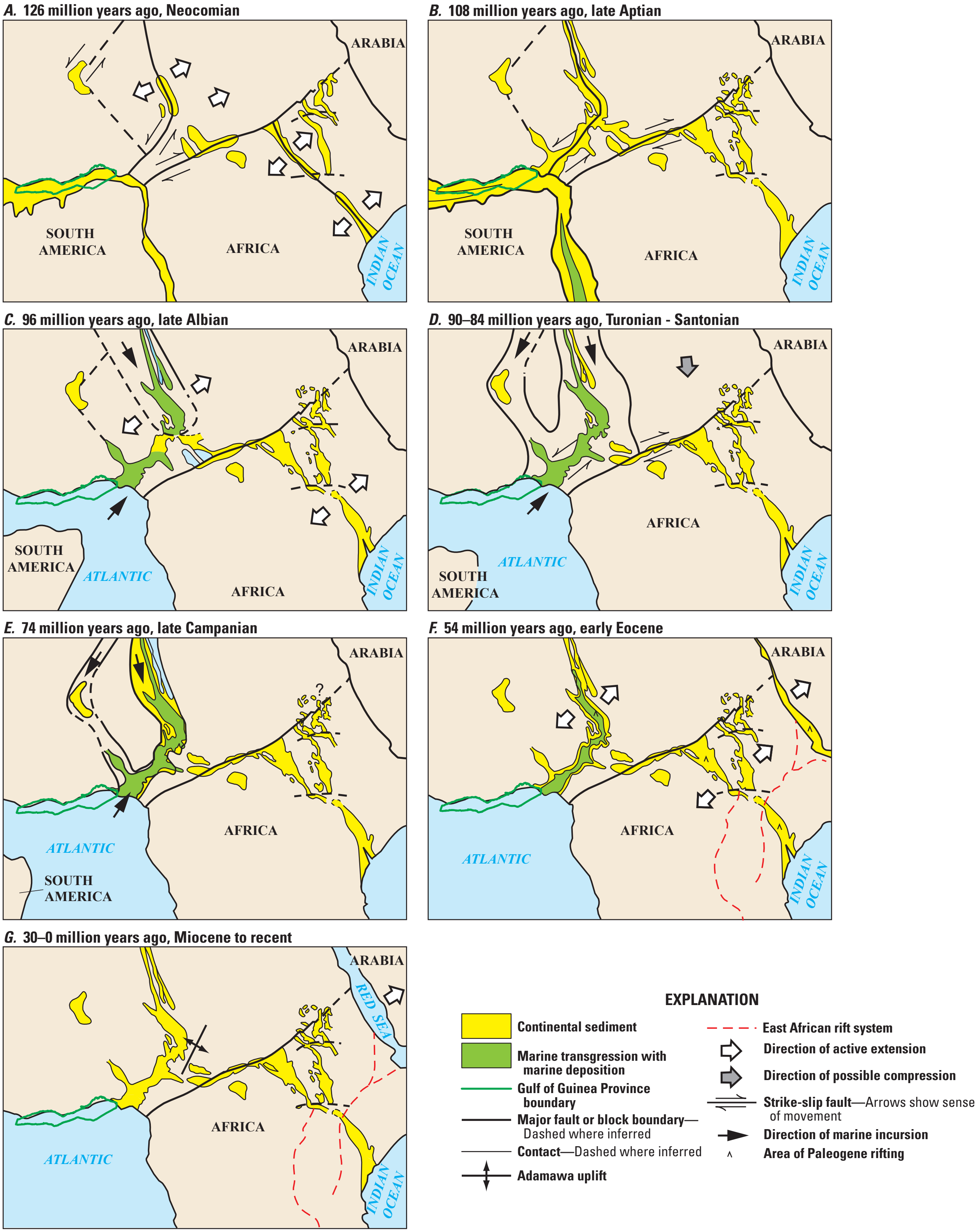


Figure 5. Paleotectonic maps showing the evolution of continental margins of west Africa and South America. Modified from Genik (1993). Dates are consistent with U.S. Geological Survey Geological Names Committee, 2010.

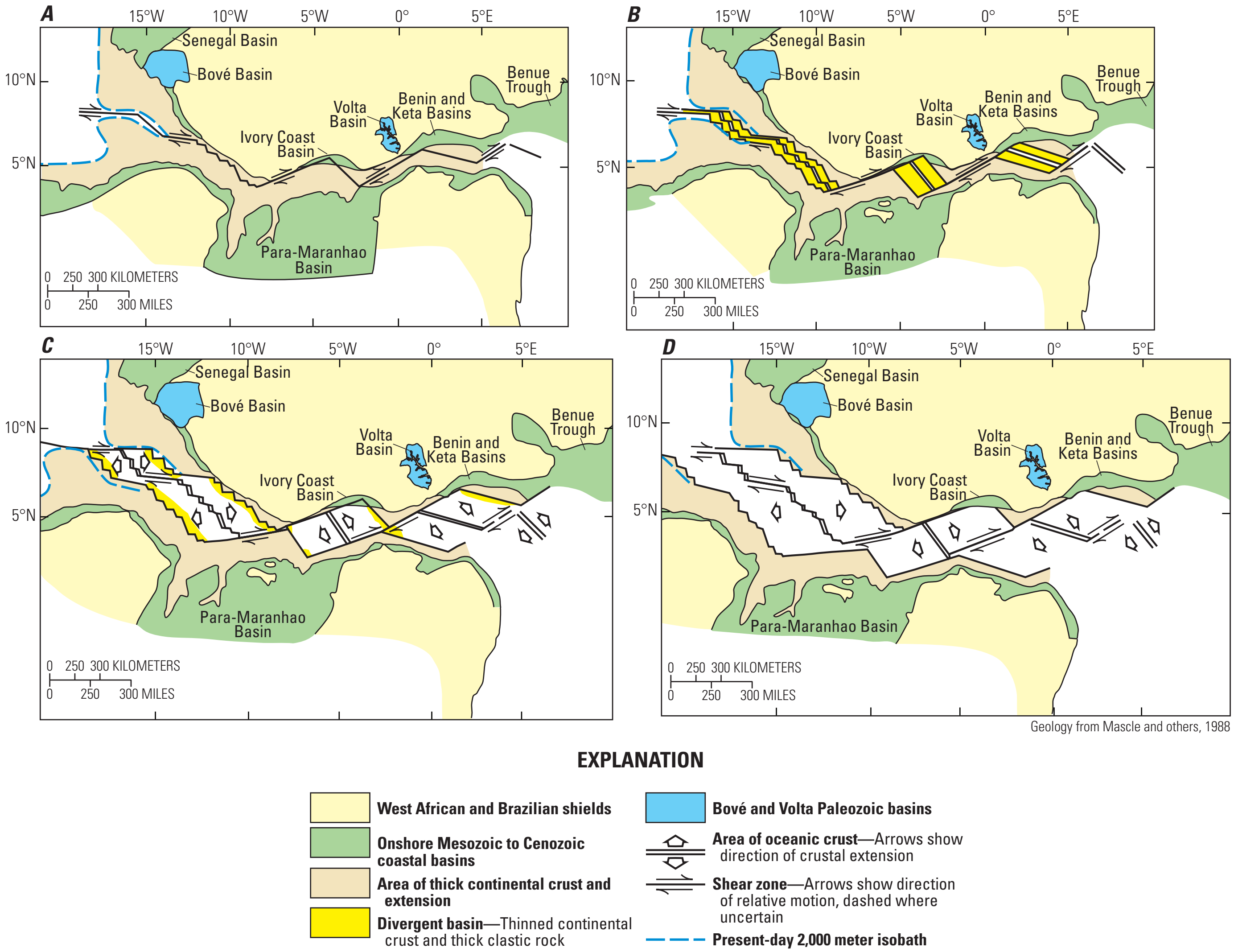


Figure 6. Schematic Cretaceous stages in the Mesozoic breakup of Africa and South America and the tectonic evolution of the Equatorial Atlantic; principal basins labeled. Para-Maranhao Basin in present-day Brazil. *A*, Hauterivian, 125 Ma; *B*, early Albian, 110 Ma; *C*, late Albian, 100 Ma; *D*, Santonian, 85 Ma. Modified from Mascle and others (1988). Dates are consistent with U.S. Geological Survey Geological Names Committee, 2010.

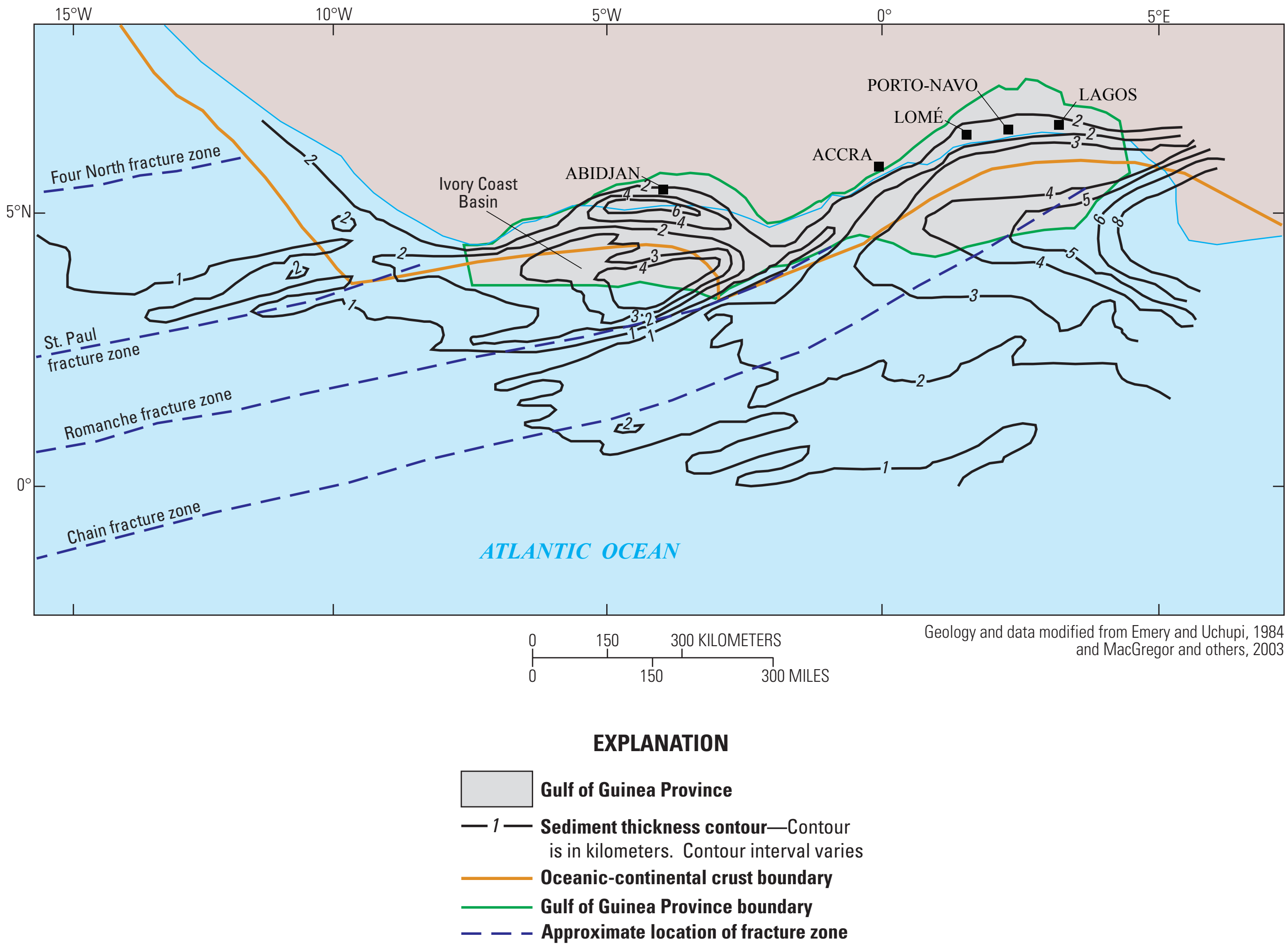


Figure 7. Major fracture zones, sediment thickness, and oceanic-continental crust boundary of the present-day Gulf of Guinea Province. Modified from Emery and Uchupi (1984) and MacGregor and others (2003).

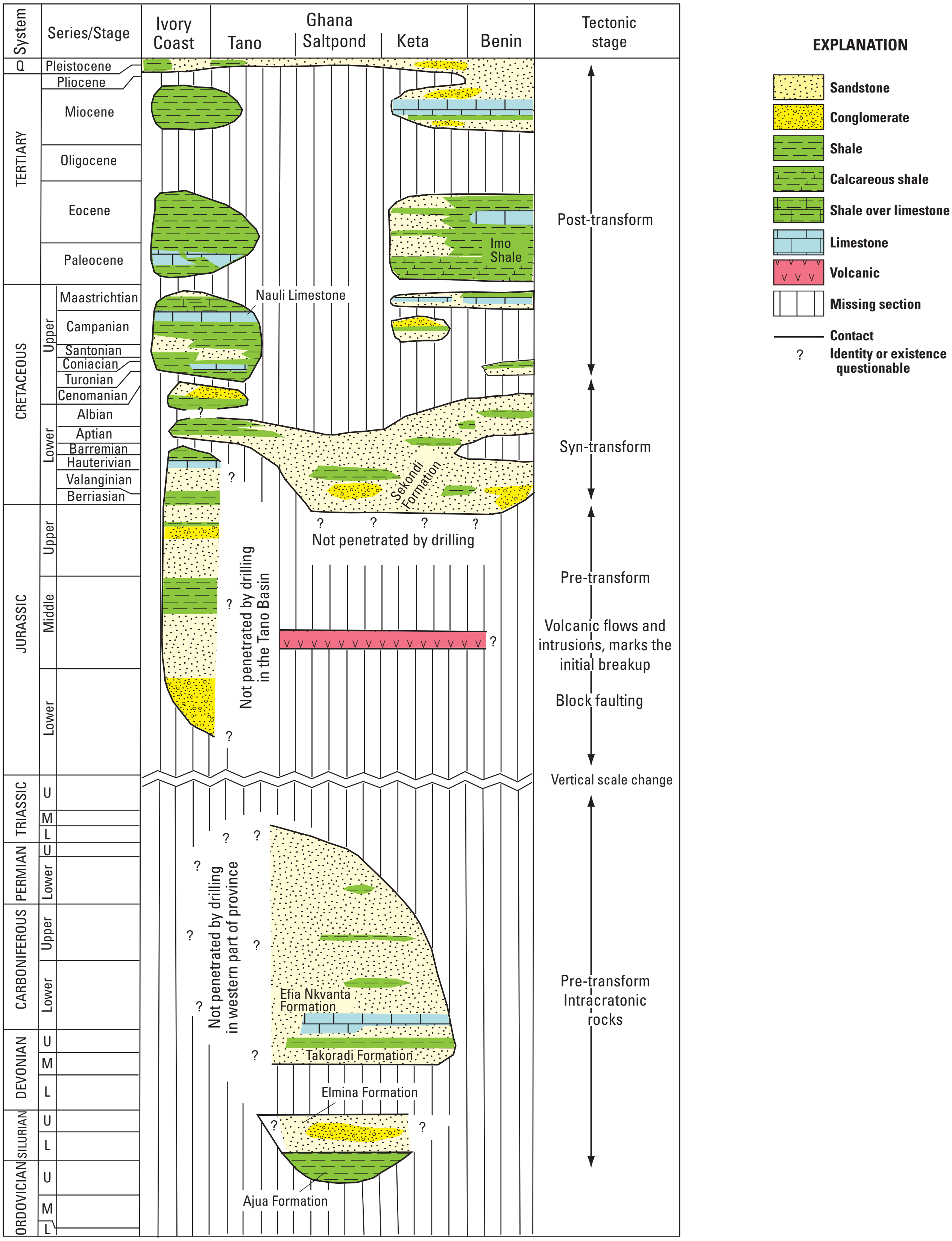


Figure 8. Generalized stratigraphic column showing age, lithology, tectonic stage, and stratigraphic position of selected formations in major basins (fig. 3) of the Gulf of Guinea Province. Modified from Kjemperud and others (1992). Q, Quaternary; L, Lower; M, Middle; U, Upper.

Geology

Pretransform Stage

The pretransform section consists of Precambrian to Triassic rocks that crop out in the Volta and Tano Basins of Ghana (Volta Province) (fig. 3). This section has been penetrated by drilling in the Saltpond, Tano, and Keta Basins (fig. 3) in the central and eastern parts of the Gulf of Guinea Province (Dumestre, 1985; Kesse, 1986; Kjemperud and others, 1992; Tucker, 1992). For a detailed description of the pretransform rocks in the province see Brownfield and Charpentier (2006a).In the Central, Keta, and Saltpond Basins (figs. 3, 8, 9, 10) of central and eastern Ghana, the pretransform rocks range in age from Ordovician to Triassic (Kjemperud and others, 1992; Tucker, 1992). The Ordovician to Silurian lacustrine Ajua Formation consists of laminated shales. It is overlain by the fluvial and lacustrine Elmina Formation, composed of feldspathic sandstone and minor conglomerate. Both formations are present only in the Central and Saltpond Basins (Kjemperud and others, 1992). Marine Silurian rocks (Clifford, 1986), which are known to contain oil-prone black graptolitic shales in northern Africa, are widely distributed in North Africa and oceans adjacent to the modern-day African coast (fig. 11). As indicated, Silurian deposition possibly continued eastward to the Benue Trough in Nigeria.

Pretransform rocks have not been identified with certainty in the Ivory Coast Basin (fig. 3), but the basin does contain Jurassic rocks (fig. 8) consisting of thick beds of conglomerate and sandstone deposited in a continental setting. These rocks were interpreted to be older than syntransform-related volcanic rocks (Kjemperud and others, 1992).The only Paleozoic rocks observed in the Tano Basin of eastern Côte d'Ivoire and western Ghana are Lower Carboniferous siliciclastic rocks (Tucker, 1992) that were penetrated by the CTS-1 well (fig. 3). Seismic data indicate that this sequence is underlain by strata equivalent to the Ordovician and Devonian rocks in the onshore part of the Saltpond Basin and the offshore part of the Keta Basin. The Lower Carboniferous and underlying rocks in the CTS-1 well represent the western limit of Paleozoic rocks in the Gulf of Guinea Province. Similar Paleozoic rocks crop out at Cape Three Points (fig. 3) and are present offshore.

Upper Jurassic pretransform sedimentary rocks have not been identified with certainty in the Keta Basin (figs. 3, 10) in eastern Ghana (Kjemperud and others, 1992). The lower part of continental Upper Jurassic to Lower Cretaceous rocks (fig. 10) (the Sekondi Formation; not shown on fig. 10) may correlate with the Upper Jurassic to Lower Cretaceous Ise Formation in the offshore part of the Benin Basin (fig. 12) (Elvsborg and Dalode, 1985). This portion of the section may represent the uppermost part of this stage. The Ise Formation contains conglomerate, sandstone, and shale that were deposited in continental and deltaic environments.

The pretransform rocks in the Benin or Dahomey Embayment are represented by the lower part of the Ise Formation (Dumestre, 1985; Elvsborg and Dalode, 1985; MacGregor and others, 2003). The Upper Jurassic to Neocomian Ise Formation (fig. 12), as much as 2,000 m thick, is composed of sandstone, shales, and conglomerate deposited in fluvial and deltaic environments. Drilling has not penetrated the base of the formation, but seismic data indicate that it directly overlies basement rocks in the Benin Basin.

Syntransform Stage

Data on the age of volcanic intrusives associated with initial block faulting in southern Sierra Leone (northwest of Liberia), Liberia, and Ghana (fig. 3) indicate that faulting started no later than the Middle Jurassic and may be as old as Early Jurassic (Dumestre, 1985; Kjemperud and others, 1992). Continental syntransform rocks in the Ivory Coast Basin (figs. 3, 8) also show evidence that volcanic and fault activity may have started in the Early Jurassic. Block faulting and graben filling characterized the initial stage of tectonism, followed by transform or extensional faulting in the Gulf of Guinea. See Brownfield and Charpentier (2006a) for a detailed discussion of the syntransform stage.

The oldest Mesozoic syntransform sedimentary rocks are continental Jurassic conglomerate and sandstone (Dumestre, 1985), with thicknesses as much as 2,000 m in the Ivory Coast Basin (figs. 3, 8). A comparable sequence has not been penetrated by drilling in Ghana, indicating a period of nondeposition or erosion (or both) in that area (Kjemperud and others, 1992).

During Neocomian, Aptian, and probably early and middle Albian time, more than 5,000 m of syntransform sediment (Chierici, 1996) was deposited in continental to marginal-marine environments in the Ivory Coast Basin (fig. 8). The oldest marginal-marine strata are upper Albian shales. The lack of evaporites in the Lower Cretaceous section indicates that in the Gulf of Guinea Province the syntransform sediments were deposited in a humid equatorial climate.

Lowermost Cretaceous syntransform sediments in the Tano and Saltpond Basins (figs. 3, 9) were deposited under mostly continental conditions (Kjemperud and others, 1992; Tucker, 1992) resulting in interbedded sandstone, shale, and limestone (figs. 8, 9). The environment became mostly marine during the late Aptian to early Albian, resulting in a syntransform section of alternating sandstone and shale with some black shale, coarse sandstone, conglomerate, and minor limestone.

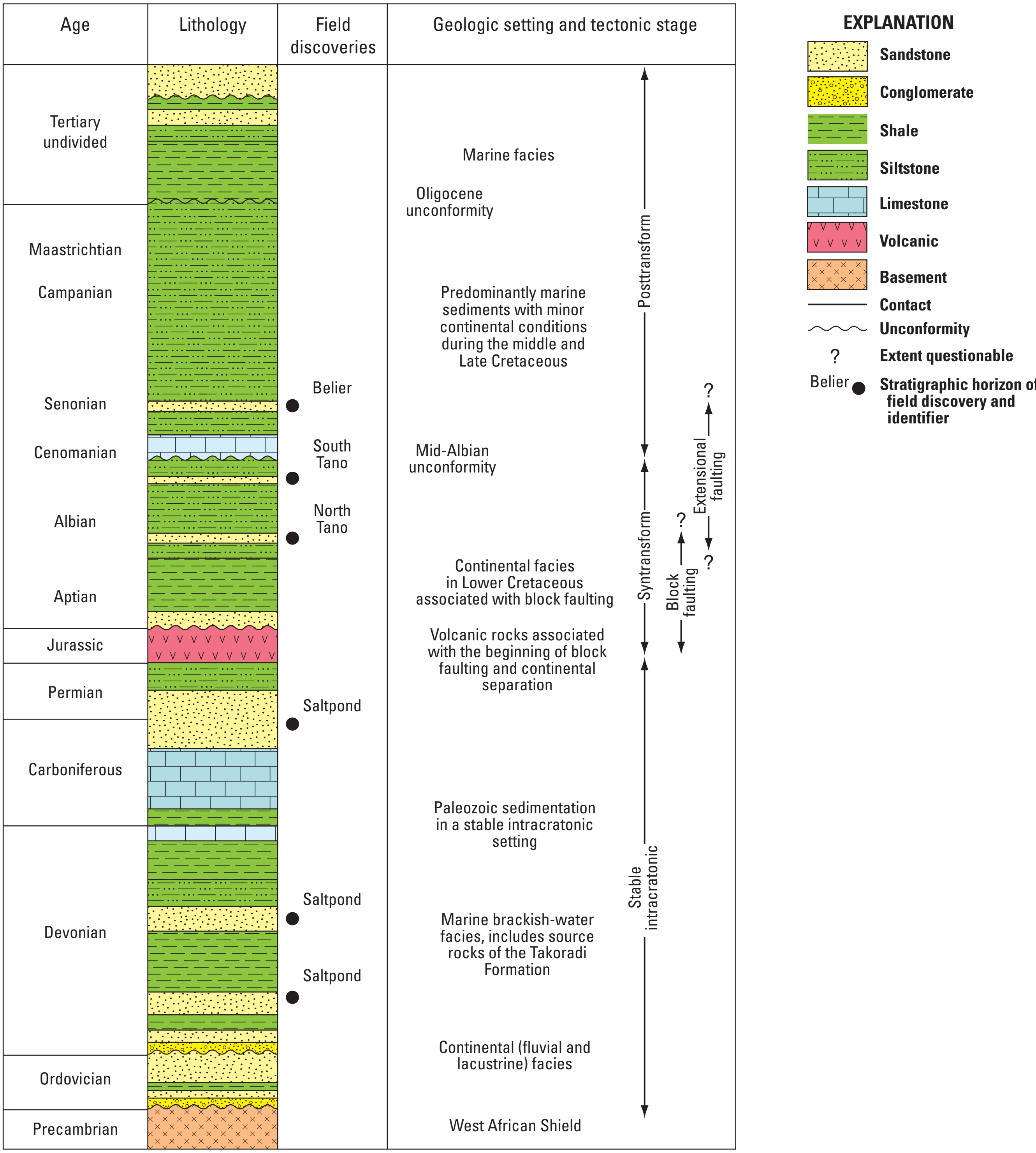


Figure 9. Generalized composite stratigraphy of offshore and onshore parts of the Saltpond and Tano Basins, Ghana, Gulf of Guinea Province, Africa. Age, lithology, approximate stratigraphic horizon of field discoveries, geologic setting, and tectonic phase are shown. See figure 4 for the location of field discoveries. The middle and upper parts of the Devonian contains marine source rocks in the Takoradi Formation. See figure 8 for stratigraphic position of selected formations. Senonian Stage is considered to contain the Coniacian, Santonian, Campanian, and Maastrichtian. Modified from Tucker (1992). Cretaceous stage boundaries were not shown by Tucker (1992).

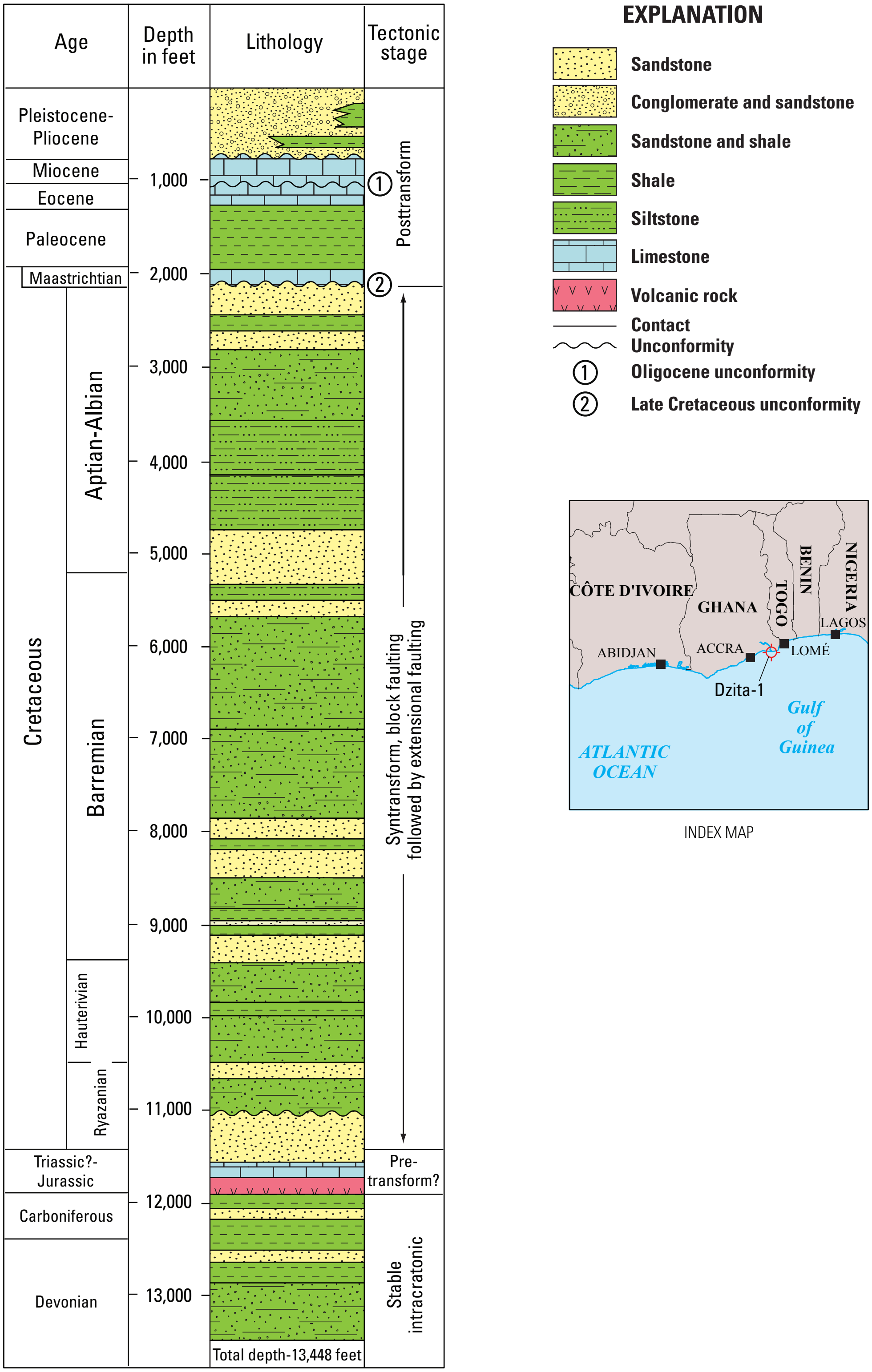


Figure 10. Generalized stratigraphy of drill hole Dzita-1, Keta Basin, eastern Ghana, showing age, depth, lithology, and tectonic phase. (Ryazanin is a stage in the British Lower Cretaceous that is roughly equivalent to Berriasian.) Jurassic volcanic rocks represent the onset of block faulting in the province. Late Cretaceous unconformity at the base of the Maastrichtian (circled 1) represents a major period of erosion; it is estimated that more than 1,300 m of Upper Cretaceous (Albian to Campanian) rocks were removed. The middle Oligocene unconformity (circled 2) represents a period of erosion during which as much as 390 m of Tertiary rocks were removed. Modified from Kjemperud and others (1992).

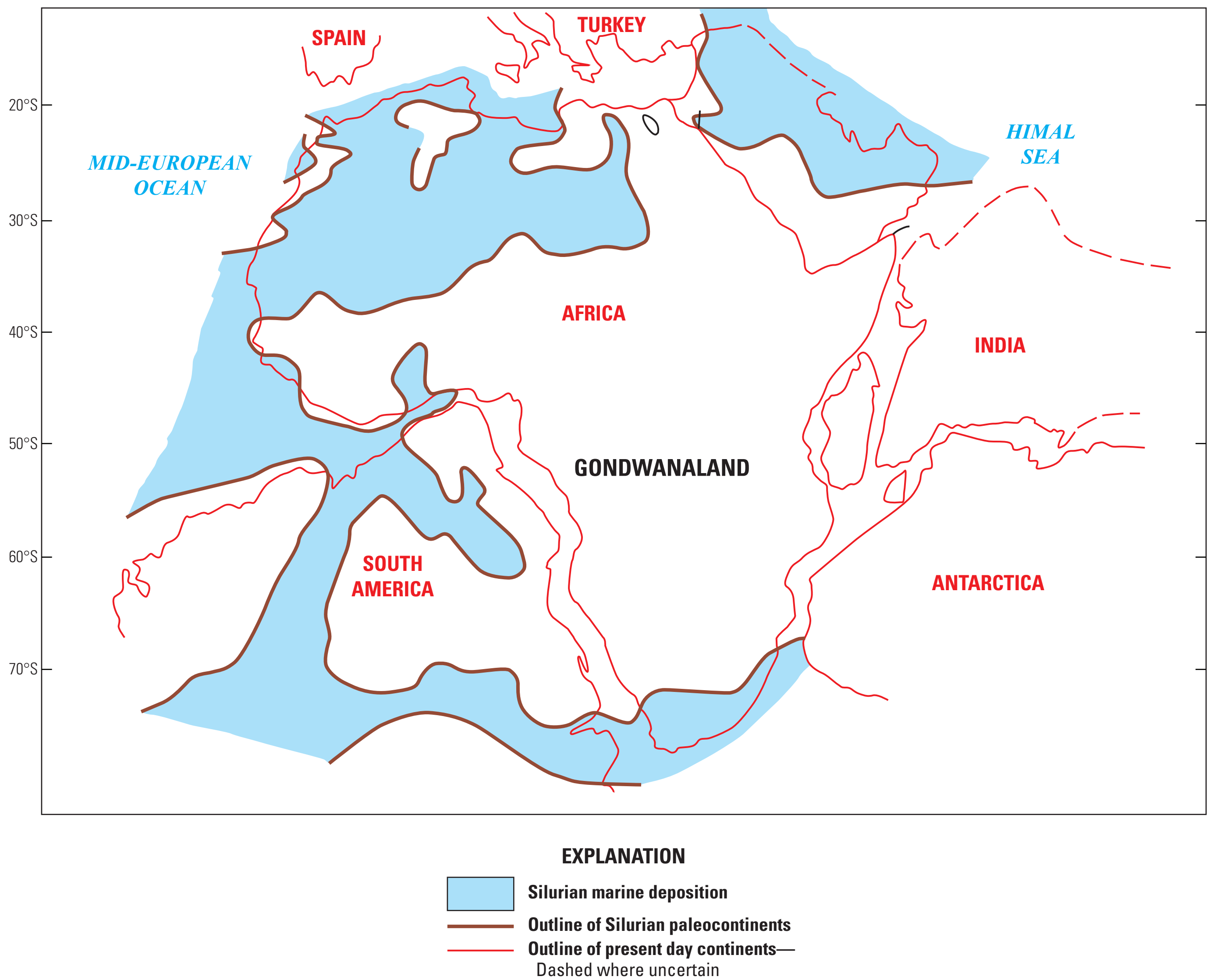


Figure 11. Paleogeographic reconstruction of the Silurian Period showing relative positions of paleocontinents and areas of deposition of marine Silurian rocks, of which oil-prone graptolitic shales constitute a major part. Outline of present day continents shown in relative position with areas of known Silurian rocks. Modified from Clifford (1986).

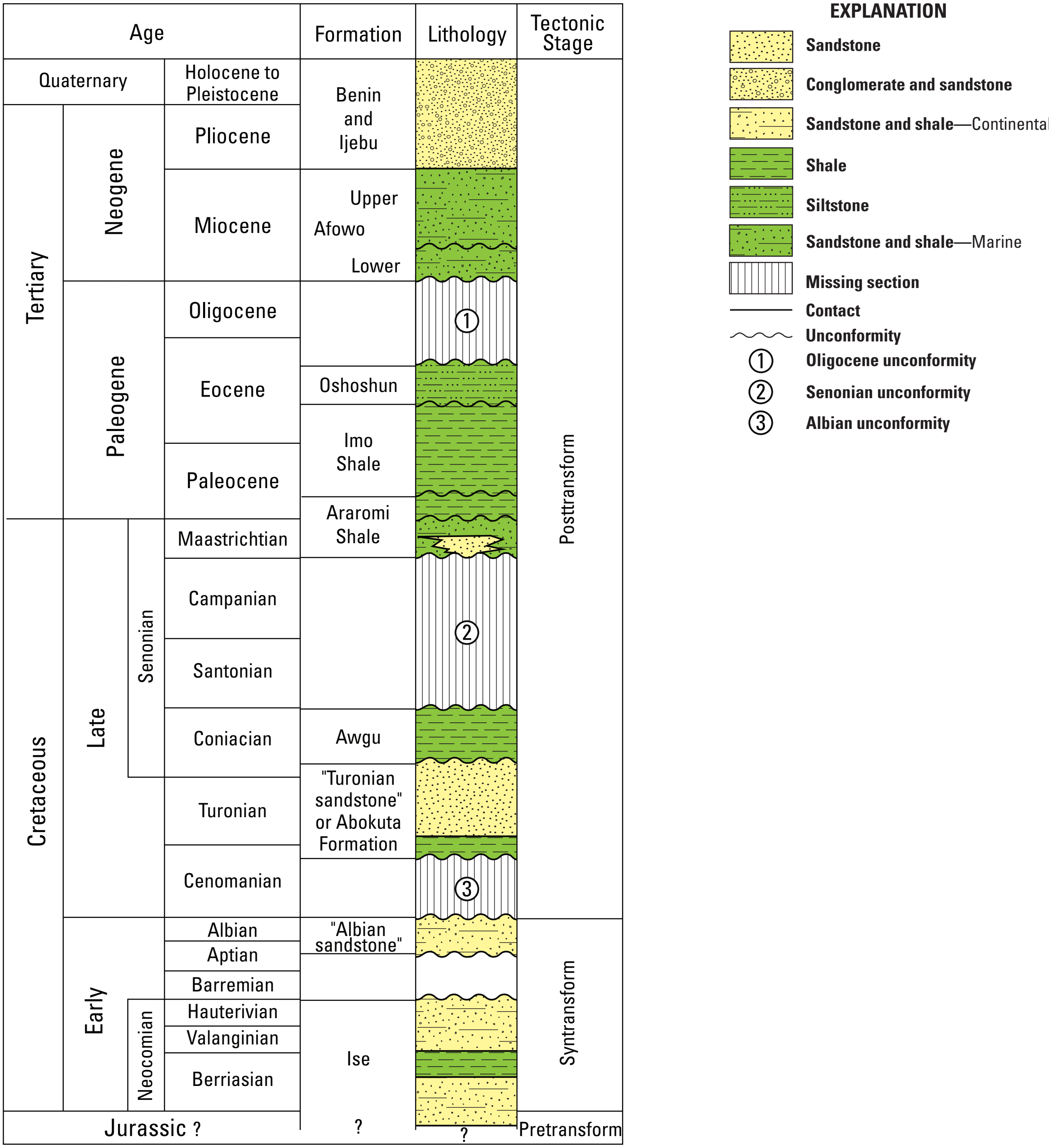


Figure 12. Generalized stratigraphy of offshore part of Benin Basin, Gulf of Guinea Province. The lower part of the Ise Formation is considered to be Upper Jurassic and part of the pretransform tectonic phase. The Turonian sandstone is known as the Abeokuta Formation in Benin. Modified from Elvsborg and Dalode (1985) and MacGregor and others (2003).

The Keta Basin of eastern Ghana (figs. 8, 10) contains syntransform rocks of Early Cretaceous age (Kjemperud and others, 1992) in both offshore and onshore areas; these rocks were deposited in a continental environment. During the earliest Cretaceous the basin underwent gradual subsidence, block faulting, and graben filling followed by extensional faulting. The Aptian to Albian rocks (fig. 10) are characterized by marine sandstone and shale with some black shale, coarse sandstone and conglomerate, and minor limestone (Kjemperud and others, 1992). Graben filling continued until the middle of the Cenomanian, when uplift of the basin brought about extensive erosion and the peneplanation of the Gulf of Guinea Province. The Campanian is represented by marine sandstone, shale, and minor limestone and conglomerate (fig. 8). In Dzita-1 well (fig. 10), the unconformity at the base of the Maastrichtian represents a major period of erosion, during which it is estimated that more than 1,300 m of Upper Cretaceous rocks were removed (Kjemperud and others, 1992).

In the Benin Basin (fig. 3), syntransform rocks are represented by the Neocomian part of the Ise Formation (fig. 12); they include sandstone, shale, and conglomerate deposited in fluvial, lacustrine, and deltaic environments (Dumestre, 1985; Elvsborg and Dalode, 1985; MacGregor and others, 2003). The upper part of the Ise Formation contains lacustrine algae similar to those present in the lacustrine Bucomazi Formation of the Lower Congo Basin (Haack and others, 2000; Brownfield and Charpentier, 2006b) in the West-Central Coastal Province of West Africa (fig. 4). The Ise Formation is unconformably overlain by the transgressive “Albian sandstone” (fig. 12), representing the upper boundary of the syntransform stage in the Benin Basin (Elvsborg and Dalode, 1985).

The end of the syntransform stage is delineated by a major unconformity that separates it from the posttransform marine rocks of the uppermost Albian and Cenomanian (Dumestre, 1985; Kjemperud and others, 1992; Chierici, 1996; MacGregor and others, 2003). This unconformity is also readily recognized in the Brazilian marginal basins, which supports the interpretation that the two continents were adjacent to one another and shared similar geologic histories during the Early Cretaceous.

Posttransform Stage

The posttransform stage rocks in the Gulf of Guinea Province consist predominantly of Cenomanian to Holocene marine sandstone, shale, and minor carbonate rocks (fig. 8) deposited in alternating regressions and transgressions (Dumestre, 1985; Chierici, 1992; Kjemperud and others, 1992; MacGregor and others, 2003) that resulted in several Upper Cretaceous and Tertiary unconformities (figs. 8, 9, 10, 12). In general, continental-margin tectonics of the province’s posttransform stage were driven by thermal subsidence (Kjemperud and others, 1992). See Brownfield and Charpentier (2006a) for a detailed discussion of the posttransform stage.

A marine transgression in the Ivory Coast Basin in the early Cenomanian (fig. 8) signaled the beginning of the posttransform stage, resulting in the deposition of limestone on fault-block crests and black shale and turbidites in the grabens (Dumestre, 1985; Chierici, 1996). Paleontological evidence indicates restricted water circulation and low-oxygen content (Chierici, 1996). During the regression, more than 3,000 m of middle and upper Cenomanian sediments were deposited in the central and western parts of the basin, as evidenced by strata penetrated in the Attoutu-1 well (fig. 3) in the northwestern part of the basin (Chierici, 1996). In the Turonian, a major transgression established the first communication between Atlantic and Tethyan waters. Paleontological analysis indicates that restricted water circulation and a low-oxygen content continued through the Turonian (Chierici, 1996). An episode of intense deformation occurred in the Benue Trough (fig. 6) at the end of the Santonian that was reflected by erosion and the development of a major unconformity (fig. 13, Senonian unconformity) in the eastern half of the Ivory Coast Basin (Dumestre, 1985; Chierici, 1996). Campanian and Maastrichtian rocks are predominantly sandstone and shale.

The Paleocene succession represents a major transgression in the Ivory Coast Basin, where it consists of glauconitic shale with sandy shale and minor limestone. These rocks, in turn, are overlain by lower and middle Eocene shale and marl with thin beds of limestone (Chierici, 1996). A major unconformity (fig. 13) developed in Oligocene time. Marine Miocene rocks lie above this unconformity in the offshore part of the Ivory Coast Basin, and no Oligocene rocks have been identified in offshore exploration wells.

The Tano Basin is located in the easternmost part of the Ivory Coast Basin (fig. 3), and the posttransform period in the Tano Basin generally has the same tectonic and stratigraphic history as the rest of the Ivory Coast Basin. Posttransform continental margin tectonism was driven by thermal subsidence, beginning in the Cenomanian (fig. 9) with the first marine transgression into the Gulf of Guinea Province. Marine waters most likely inundated the remaining syntransform block-faulted terrain. The Cenomanian rocks include sandstone, shale, siltstone, mudstone, and limestone (Kjemperud and others, 1992; Tucker, 1992); black shale and limestone were deposited on the crests of the horsts, whereas turbidites accumulated in the grabens. Cenomanian to Maastrichtian rocks (fig. 9) include marine sandstone, shale, limestone, and minor conglomerates (Kjemperud and others, 1992; Tucker, 1992)). Major unconformities bound the Cenomanian to Maastrichtian rocks in the Tano Basin as in the Ivory Coast Basin. The overlying unconformable Tertiary rocks are marine sandstone, shale, and limestone. The regional Oligocene unconformity is present in the Tano Basin (fig. 9) separating Miocene from the underlying Eocene rocks.

Posttransform rocks range in age from Campanian to Holocene in the Keta Basin (figs. 8, 10, 14). Campanian strata, including marine and continental conglomerate, sandstone, shale, and limestone (fig. 8) unconformably overlie Albian syntransform rocks and are unconformably overlain by

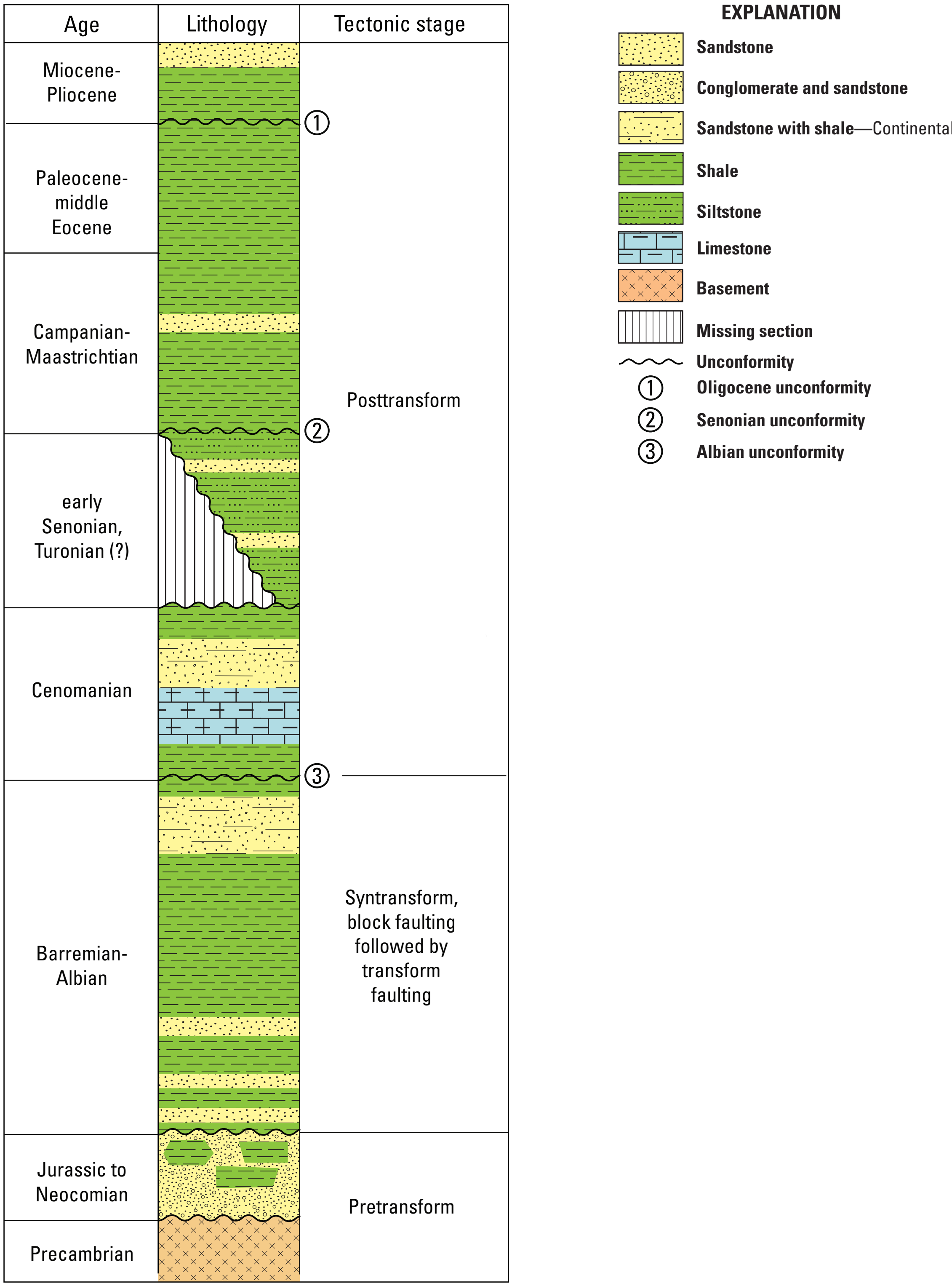


Figure 13. Generalized stratigraphy of rocks in the central and western parts of Ivory Coast Basin, Gulf of Guinea Province, Africa, showing age, lithology, and tectonic stage. Pretransform rocks were deposited in continental environments, syntransform rocks in continental to marginal-marine environments, and posttransform rocks in marginal marine to open-marine environments. Exploration drilling has not reached rocks older than Jurassic in the central and western parts of the Ivory Coast Basin. Modified from Chierici (1996).

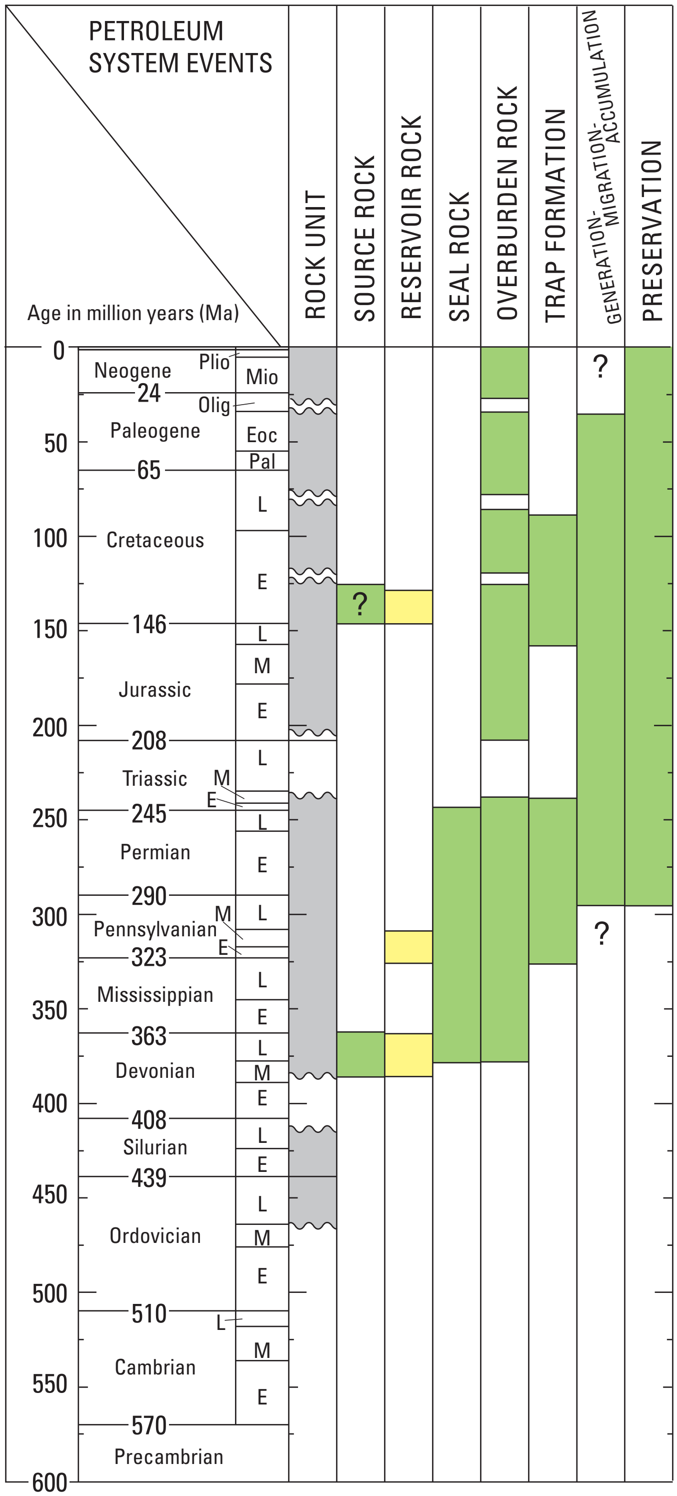


Figure 14. Events chart for the Lower Paleozoic Petroleum System (717301) in Saltpond, Keta, and Tano Basins, Gulf of Guinea Province, Africa. Gray, rock units present; yellow, age range of reservoir rock; green, age ranges of source, seal, and overburden rocks and the timing of trap formation and generation, migration, and preservation of hydrocarbons; wavy line, unconformity. Divisions of geologic time conform to dates in U.S. Geological Survey Geologic Names Committee (2010). Ma, million years ago; Plio, Pliocene; Mio, Miocene; Olig, Oligocene; Eoc, Eocene; Pal, Paleocene, L, Late; E, Early; M, Middle; ?, uncertain.

Maastrichtian rocks. The Maastrichtian includes limestone and shale with sandstone and claystone deposited in a marine environment; these strata grade into continental clastic units eastward toward the Benin Basin. Tertiary posttransform rocks, which unconformably overlie the Maastrichtian rocks, include Paleocene to Eocene marine shale interbedded with sandstone, siltstone, and limestone. These rocks are separated from the upper Miocene marine sandstone, conglomerate, shale, and limestone (fig. 9) by a major Oligocene to Miocene unconformity. During the erosional period represented by this unconformity, as much as 365 m of Tertiary rocks were removed (Kjemperud and others, 1992), as evidenced by the stratigraphic section penetrated in the Dzita-1 and Keta-1 wells (figs. 3, 10, 15). An unconformity separates the upper Miocene and lower Pliocene in parts of the onshore and shallow shelf (fig. 9). The Pliocene to Holocene offshore units consist of unconsolidated sand and mud.

The Cenomanian to Santonian part of the posttransform stage in the Benin Basin and Dahomey Embayment (fig. 3) was influenced by transform or extensional faulting and was also affected by deformation that took place during the Santonian in the Benue Trough to the east (fig. 6) (Elvsborg and Dalode, 1985). These episodes of tectonic activity resulted in the development of the Senonian unconformity in the Benin Basin (fig. 12).

The Coniacian Awgu Formation (fig. 12), which is present over most of the Benin Basin, unconformably overlies the “Turonian sandstone” and consists of dark-gray calcareous shale interbedded with calcareous siltstone and fine-grained sandstone that was deposited in an anoxic marine environment below the Senonian unconformity (fig. 12). A depositional hiatus from the late Eocene through the Oligocene resulted in a major unconformity between the Eocene and Miocene (fig. 12).

Total Petroleum Systems and Petroleum Occurrence in Gulf of Guinea Province, West Africa

At least five total petroleum systems exist in the Gulf of Guinea Province (7183): (1) Lower Paleozoic Total Petroleum System (TPS), consisting of Devonian source rocks and Devonian to Lower Cretaceous reservoir rocks (fig. 14); (2) Lower Cretaceous TPS, consisting of Lower Cretaceous lacustrine source rocks and Cretaceous reservoir rocks (fig. 15); (3) Middle Albian Terrestrial TPS, consisting of gas-prone source rocks and Albian reservoir rocks; (4) Upper Albian TPS, consisting of marine-transgressive oil-prone source rocks and Albian reservoir rocks; and (5) Cenomanian-Turonian TPS, consisting of marine oil-prone source rocks and Albian to Upper Cretaceous reservoir rocks.

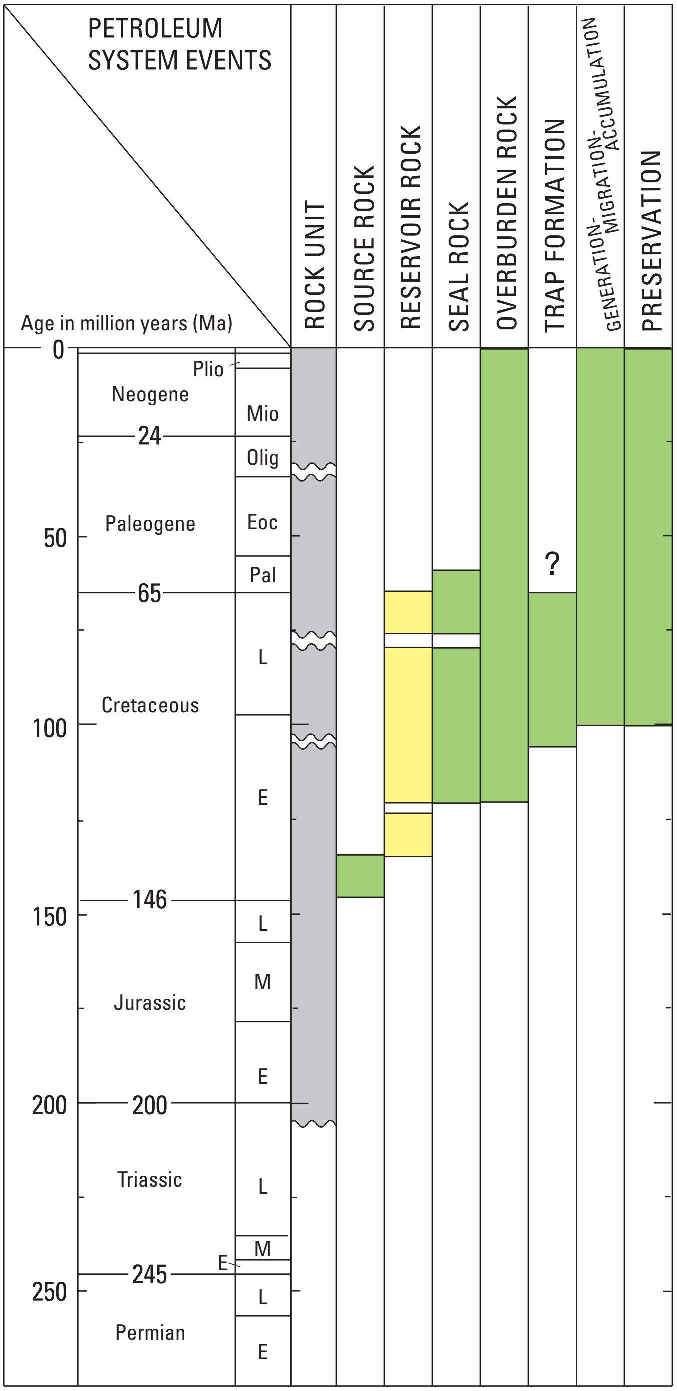


Figure 15. Events chart for the Lower Cretaceous Total Petroleum System (717301) in the Ivory Coast, Tano, Keta, and Benin Basins, Gulf of Guinea Province, Africa. Gray, rock units present; yellow, age range of reservoir rock; green, age ranges of source, seal, and overburden rocks and the timing of trap formation and generation, migration, and preservation of hydrocarbons; wavy line, unconformity. Divisions of geologic time conform to dates in dates in U.S. Geological Names Committee (2010). Ma, million years ago; Plio, Pliocene; Mio, Miocene; Olig, Oligocene; Eoc, Eocene; Pal, Paleocene, L, Late; E, Early; M, Middle; ?, uncertain.

The three youngest systems were combined into the Cretaceous Composite TPS (fig. 16) consisting of Albian to Turonian marine and terrestrial source rocks and Cretaceous reservoir rocks.

Only limited exploration and production information are available for the Lower Paleozoic TPS and Lower Cretaceous TPS. Oil production from the Lower Paleozoic TPS is limited to the Saltpond and Lomé fields (fig. 3), whereas Lower Cretaceous TPS oils have been identified only in Upper Cretaceous tar sand and oil seeps at Cape Three Points and the Dahomey embayment.

Source Rocks

Source rocks for the Lower Paleozoic TPS are organic-rich brackish marine shale in the Middle to Upper Devonian Takoradi Formation (fig. 8) in the Saltpond field (fig. 3). Lomé field oils are obtained from these shales (MacGregor and others, 2003), and seismic data indicate that they are preserved in the Tano Basin (Tucker, 1992), although potential targets were untested as of 2011.

The Lower Cretaceous TPS contains lacustrine source rocks deposited in early rift grabens in the central and eastern parts of the province. This depositional origin is indicated by the presence of lacustrine oils from Upper Cretaceous tar sand and oil seeps in areas west of Cape Three Points in western Ghana, as well as in the Dahomey Embayment. Neocomian Ise Formation source rocks encountered in the Ise-2 well (fig. 3) have been correlated with Upper Cretaceous oil seeps and tar sands in the northern Dahomey Embayment. The Ise Formation (fig. 12) source rocks contain Type I kerogen with total organic carbon (TOC) content of as much as 4 weight percent and hydrogen index values greater than 500 milligrams per gram (mg/g) in the organically richest intervals. Neocomian lacustrine shale has geochemical characteristics that are similar to geochemical characteristics of the Lower Cretaceous lacustrine source rocks of the Bucomazi Formation in the Congo Delta. Lower Cretaceous lacustrine rocks are identified as far west as the Ivory Coast Basin and may contain source rocks.

The principal source rocks of the Cretaceous Composite TPS are Albian, Cenomanian, and Turonian marine shale with Type II and II-III oil-prone kerogen and Type III terrestrial kerogen. Lower to middle Albian Type III source rocks were identified in the Ivory Coast (figs. 8, 13) and Tano Basins (figs. 8, 9) by MacGregor and others (2003). These organic-rich sediments were deposited in fluvial and deltaic environments in Lower Cretaceous grabens. In the Ivory Coast Basin as much as 5,000 m of Lower Cretaceous continental to marginal-marine sediment was deposited in grabens (Chierici, 1996). Similar source rocks should be present in the Keta (Kjemperud and others, 1992) and Benin Basins (figs. 8, 10). Worldwide anoxic-ocean conditions during the Cenomanian resulted in the deposition of Cenomanian to Turonian black-shale source rocks in the Ivory Coast and Tano Basins. These source rocks contain more than 10 weight percent TOC consisting of Type II

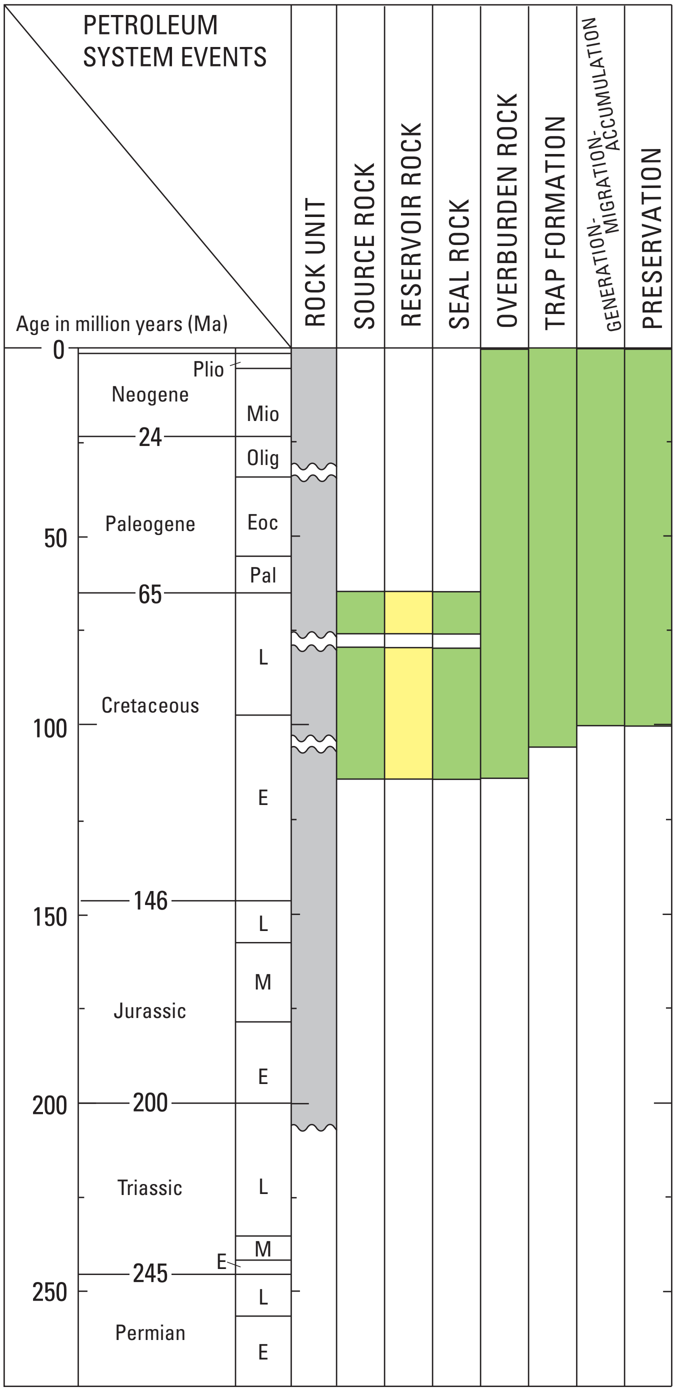


Figure 16. Events chart for the Cretaceous Composite Petroleum System (717301) and the Coastal Plain and Offshore Assessment Unit in the Ivory Coast Basin, Gulf of Guinea Province, Africa. Gray, rock units present; yellow, age range of reservoir rock; green, age ranges of source, seal, and overburden rocks and the timing of trap formation and generation, migration, and preservation of hydrocarbons; wavy line, unconformity. Divisions of geologic time conform to dates in U.S. Geological Survey Geological Names Committee (2010). Ma, million years ago; Plio, Pliocene; Mio, Miocene; Olig, Oligocene; Eoc, Eocene; Pal, Paleocene, L, Late; E, Early; M, Middle; ?, uncertain.

kerogen. In contrast, the Dahomey Embayment and Benin Basin are characterized by nonmarine to marginal-marine conditions resulting in the deposition of middle Cretaceous gas-prone source rocks containing Type III kerogen (Chierici, 1996). The Coniacian Awgu Formation and the Maastrichtian Araromi Shale (fig. 12) contain marine source rocks in the offshore part of the Benin Basin. These source rocks, which contain Type II and Type II-III kerogen with TOC contents ranging from 2 to more than 5 weight percent, were originally deposited from the northwestern extension of the Niger Delta westward to the Keta Basin (Haack and others, 2000). The richest source-rock intervals have hydrogen index values greater than 500 mg/g. Coniacian rocks are present in the offshore part of the Keta Basin (their fig. 17, Brownfield and Charpentier, 2006a); some of these may be source rocks.

Generation and Migration

Within the Gulf of Guinea Province, most hydrocarbon is generated from the upper Albian and Cenomanian source rocks in the Cretaceous Composite Petroleum System (fig. 16). These rocks are distributed throughout the offshore part of the province and are expected to increase in thickness and source-rock quality into deep water. Two main areas of hydrocarbon generation in the province were interpreted by MacGregor and others (2003): the offshore parts of the Ivory Coast and Tano Basins, and the offshore parts of the Keta and Benin Basins and the Dahomey Embayment (fig. 3) eastward to the Niger Delta (fig. 4) just east of the Gulf of Guinea Province. These two probable oil kitchens are present only in deep-water parts of the province where the source rocks have reached a temperature of at least 100° C and a vitrinite reflectance (R_o) of 0.6 percent (MacGregor and others, 2003). Hydrocarbon generation started in the Late Cretaceous and continues to the present in the Ivory Coast and Tano Basins (fig. 16), whereas hydrocarbon generation started in the late Miocene and continues to the present in the Keta and Benin Basins and Dahomey Embayment (fig. 3) eastward to the Niger Delta (fig. 2).

The source of hydrocarbons in the Lower Paleozoic Petroleum System in the Saltpond Basin is more problematic and may involve deeper source rocks, such as the Devonian Takoradi Formation and Lower Cretaceous lacustrine rocks. Generation most likely started in the Late Carboniferous for the Devonian Takoradi Formation and may have continued into the early Tertiary.

Examples of a burial-history curve and R_o and temperature plots of the Dzita-1 well in the Keta Basin are shown in figure 17. This well was drilled in 1973 to test the hydrocarbon potential of Devonian and Cretaceous sandstones. Figure 10 shows the stratigraphic sequence recorded in the drilling (Kjemperud and others, 1992). A model of the burial history that factors in a major Cretaceous (middle Albian) unconformity and a minor Tertiary (Oligocene) unconformity, representing intervals during which 1,300 m and 360 m of

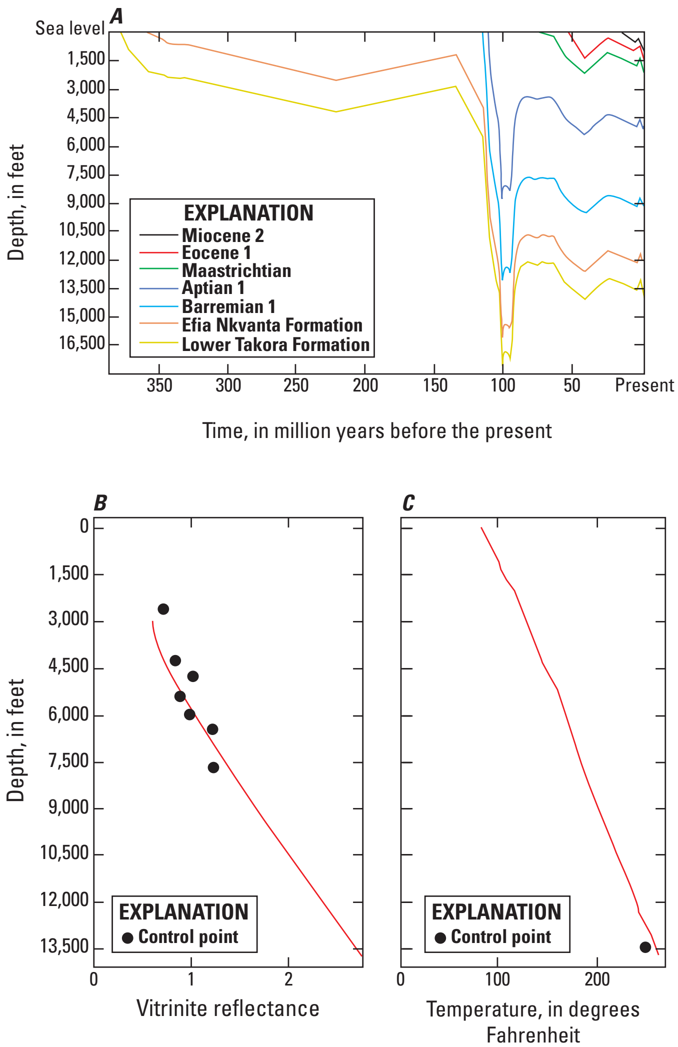


Figure 17. Modeled burial history curves and vitrinite reflectance and temperature diagrams of Dzita-1 well (figs. 3, 10) in Keta Basin, Ghana (fig. 3). Factoring in major erosion in the Cretaceous and minor erosion in the Tertiary produces a good fit with the measured R_o values. Total amount of erosion was estimated at 1,800 meters. Modified from Kjemperud and others (1992).

material were removed, respectively, indicate a good fit with the measured R_o values (fig. 15). This model is in agreement with the maturity mapping of the Cretaceous unconformity by MacGregor and others (2003), who placed the top of the oil-generation window (R_o about 0.6) at about 2,700 m depth.

At least two areas of hydrocarbon generation related to Lower Cretaceous Petroleum System lacustrine source rocks are present in the province (Haack and others, 2000; MacGregor and others, 2003). These areas are associated with oil seeps and tar-sand accumulations along Upper Cretaceous outcrops west of Cape Three Points in the onshore parts of the Ivory Coast and Tano Basins and the Dahomey Embayment (fig. 3). In particular, there are large in-place volumes of hydrocarbons in the eastern tar belt of the Dahomey Embayment. Hydrocarbon generation began in the Late Cretaceous and may be active to the present.

Reservoirs, Traps, and Seals

The oldest proven reservoir rocks in the Gulf of Guinea Province are Devonian to Carboniferous sandstone beds in the Saltpond field in Ghana (fig. 3). The Devonian sandstone reservoirs were deposited in shallow- to restricted-marine environments, whereas the Carboniferous sandstone reservoirs were deposited in fluvial environments.

Seismic data indicate that a thick Lower Cretaceous syntransform section in the offshore part of the Benin Basin (fig. 3) contains sandstone reservoir units (Elvsborg and Dalode, 1985) deposited in fluvial to deltaic environments (fig. 18). Sandstone units with favorable reservoir characteristics have been encountered in drilling in the Sémé field (fig. 3). Similar reservoir rocks may exist westward across the province; for example, as much as 5,000 m of Lower Cretaceous continental to marginal-marine sandstone and shale (fig. 8) were deposited in the Ivory Coast Basin (Chierici, 1996). Similar reservoir rocks should also be present in the Keta and Tano Basins (fig. 8).

Stratigraphic units that contain proven reservoirs in the shallow-water discoveries in the Gulf of Guinea Province are mainly late syntransform Albian sandstones and Cenomanian to Maastrichtian posttransform marginal-marine and turbidite-clastic rocks. Clastic Albian rocks are the dominant reservoir type in the Espoir and Belier fields (figs. 3, 19) in the Ivory Coast Basin and are also known in the Tano and Keta Basins.

A steep shelf began to develop along the continental margin of the Gulf of Guinea Province during the Cenomanian. MacGregor and others (2003) speculated that several south-flowing rivers supplied clastic rocks to the continental margin prior to their capture by the ancestral Niger River. These rivers—for example, a large ancestral Tano River in western Ghana and a major south-flowing river in the Benin Basin—would have drained extensive areas to the north during the early posttransform period in the province and deposited large amounts of clastic sediment during the Cenomanian to Maastrichtian (Elvborg and Dalode, 1985; Tucker, 1992; MacGregor and others, 2003). The downslope projections of deltas that formed at that time would be prospective for probable turbidite channel and ponded-turbidite sandstone reservoirs. Because the continental shelf is steep and was subjected to several lowstands along the continental margin, conditions favored the deposition of detached, deep-water sandstone units, ponded-turbidite sand, and clastic fans (figs. 18, 19). Recent seismic data indicate that large turbidite channels developed in the Ivory Coast Basin during the Maastrichtian (MacGregor and others, 2003). The presence of large turbidite channels supports the interpretation that large fans or detached sandstone bodies may lie in the deeper parts of the basin. In general, reservoirs in the early posttransform section are likely to have higher porosity and permeability than those in the syntransform section.

Seismic data also indicate that the Tertiary section has fewer reservoirs than the Cretaceous section in the Gulf of Guinea Province. Some slope fans have been identified in the

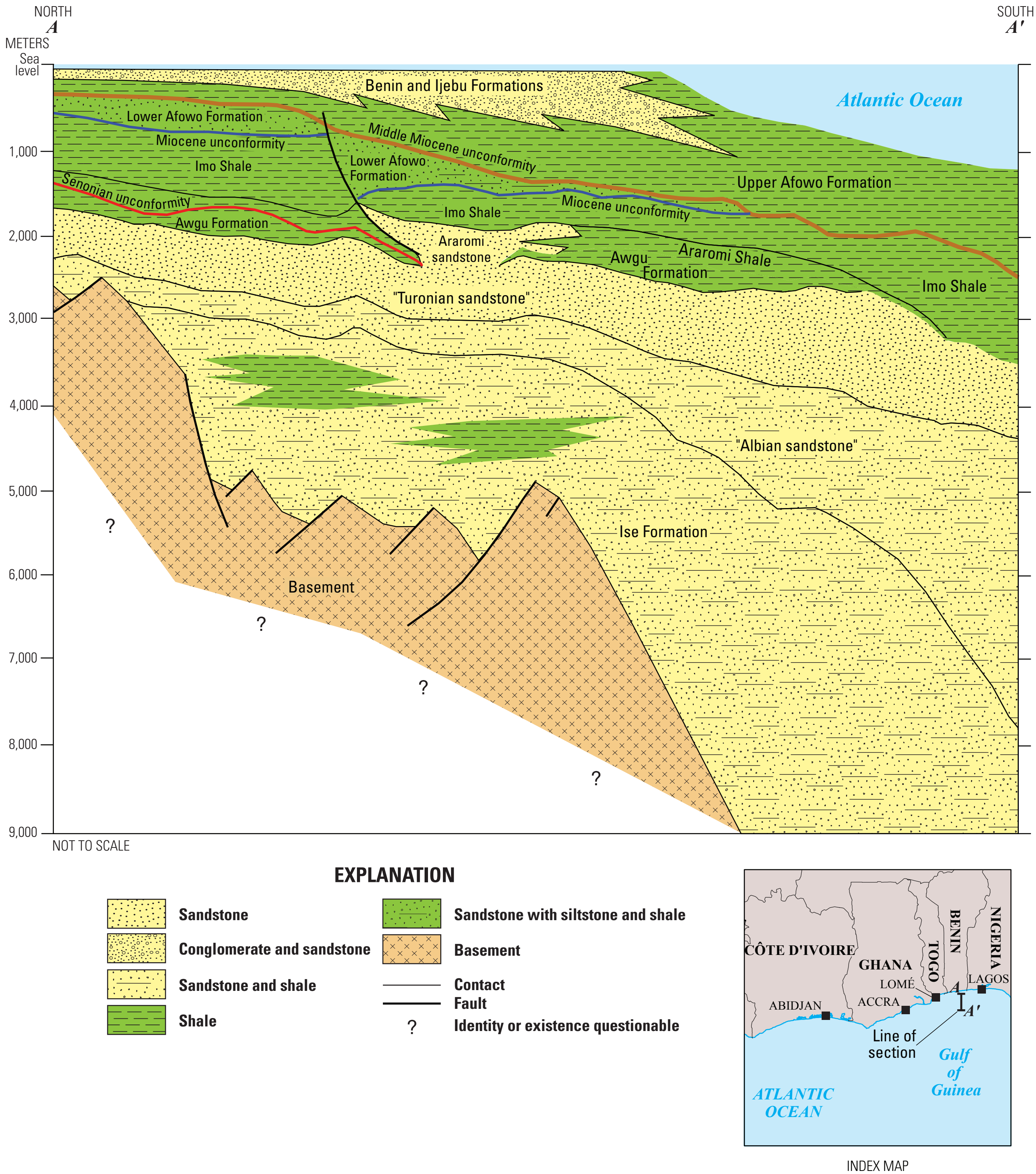


Figure 18. Generalized geoseismic cross section of offshore part of Benin Basin, Gulf of Guinea Province. Albian unconformity at base of the "Turonian sandstone" is the top of the syntransform rocks. Senonian unconformity at base of the Araromi Shale is related to tectonism in the Benue Trough. Miocene unconformity at base of the Upper Afowo Formation is related to a depositional hiatus from the Eocene to the Miocene. The Oshoshun Formation is included with Imo Shale. See figure 12 for stratigraphic positions of formations and unconformities. Modified from Elvsborg and Dalode (1985). No horizontal scale.

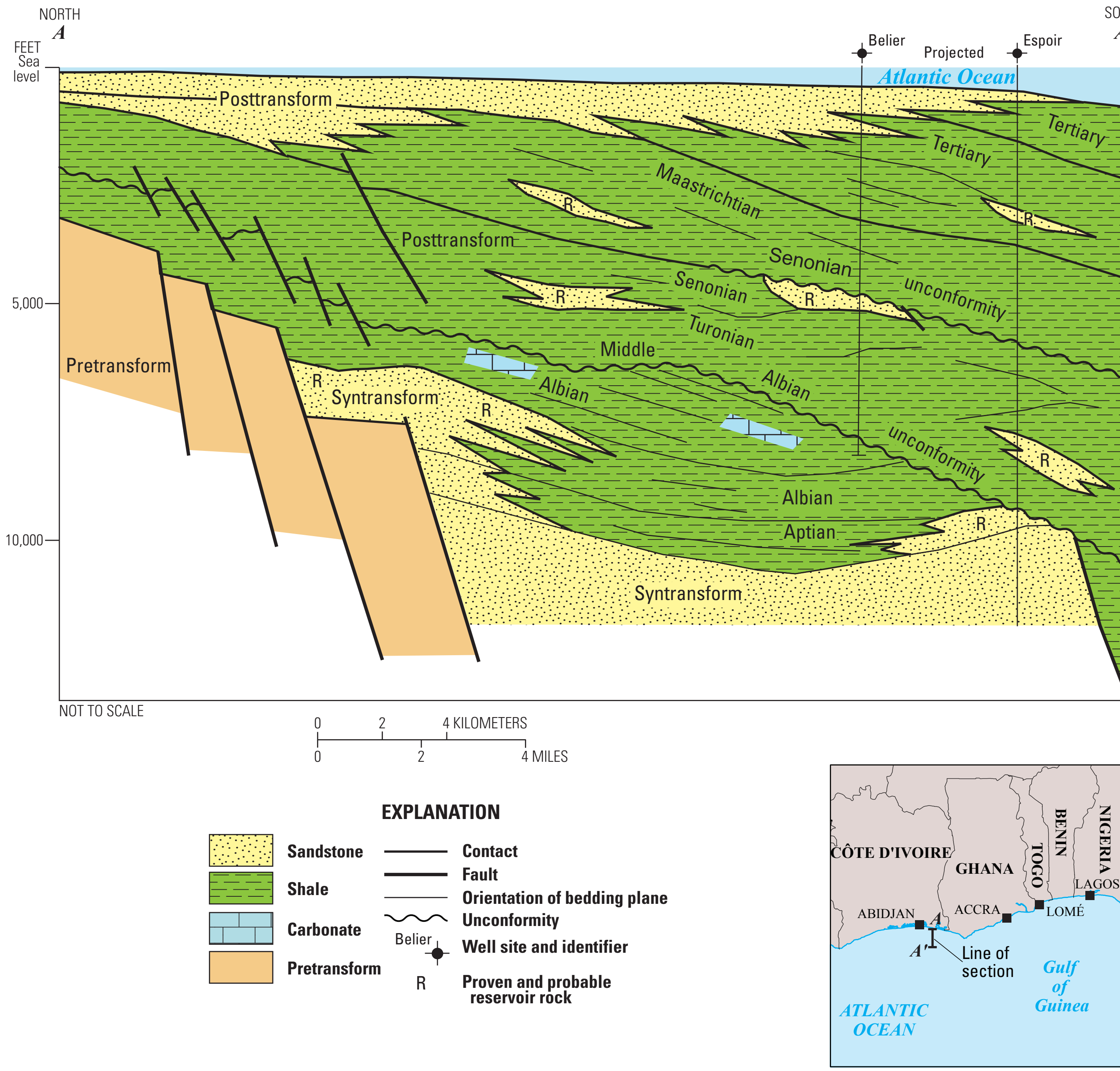


Figure 19. Schematic cross section across the Belier and Espoir fields in Ivory Coast Basin, Gulf of Guinea Province. The Senonian unconformity separates continental and marginal marine syntransform rocks from the posttransform or passive-margin rocks. Espoir and Belier field discovery wells are projected into the section (fig. 3). Modified from Clifford (1986), Kulke (1995), and Chierici (1996). Vertical exaggeration 3:1.

Araromi Shale (figs. 12, 19) (Elvsborg and Dalode, 1985) in the section overlying the regional Maastrichtian unconformity (MacGregor and others, 2003). The Araromi sandstone unit has been interpreted as a slope fan in the Benin Basin (fig. 19). Other probable reservoir rocks could be present in the deep-water part of the continental margins in the form of detached sandstone units resulting from ponded-turbidite sand (fig. 19).

The hydrocarbon traps in the Gulf of Guinea Province include pretransform traps related to fault blocks, syntransform structural and stratigraphic traps, and posttransform stratigraphic traps.

Proven hydrocarbon accumulations associated with fault-block traps (fig. 20) are in the upper part of the syntransform section throughout the Gulf of Guinea Province in shallow to moderate water depths (MacGregor and others, 2003). This trap type, which characterizes both the Espoir field (Grillot and others, 1991) and the Tano field (fig. 3) (MacGregor and others, 2003), extends offshore onto the continental slope. Fault-block traps are also present along the Romanche Fracture Zone and in the western part of the Ivory Coast Basin, including the 2001 Baobab deep-water discovery (fig. 3).

Syntransform anticlinal traps (fig. 20), detected only from seismic data and currently untested, are associated with the terminations of regional fracture zones in two areas: the offshore parts of the Dahomey Embayment and Keta Basin, and the western offshore part of the Ivory Coast Basin (MacGregor and others, 2003). Proven hydrocarbon accumulations associated with posttransitional anticlinal traps are in the Tano Basin and eastern part of the Ivory Coast Basin (fig. 3) in the Belier field.

Known hydrocarbon accumulations are associated with erosional channel-fill traps (fig. 20) in the posttransform section of the Gulf of Guinea Province in both shallow- and deep-water areas (MacGregor and others, 2003). This type of trap characterizes the Aje field of westernmost Nigeria (fig. 3), where the west end of the reservoir is sealed by a shale-filled channel. Seismic data indicate that undrilled channel-erosion traps are commonly associated with the regional Oligocene unconformity from Benin westward, in the deep-water part of the province.

Seismic data also indicate that syntransform ponded turbidites lying directly above the upper Albian unconformity in the western part of the Ivory Coast Basin (MacGregor and others, 2003) could be trapped against faults (fig. 20). Ponded turbidite traps are also observed as detached sandstone bodies in the posttransform section in the Ivory Coast, Keta, and Benin Basins, where stratigraphic trapping and updip seals are the critical factors in defining potential targets.

Untested stratigraphic traps containing ponded sand and channel sand interbedded with Cenomanian source rocks are interpreted from seismic data in the posttransform section in the Gulf of Guinea Province (fig. 20). An example of a stratigraphically sealed channel is the Maastrichtian West Tano oil discovery (figs. 3, 20).

Thick and extensive sandstone units were observed by MacGregor and others (2003) above the late Albian unconformity covering areas of more than 80 km^2 in the deep-water parts of the province, where the shelf is steeper and a greater probability exists for detached sandstone units and updip seals. Some of the high-amplitude traps associated with the late Albian unconformity may be limestone units located on syntransform highs (Kjemperud and others, 1992; MacGregor and others, 2003).

Reservoir seals associated with syntransform reservoirs are formed by both shale and faults (fig. 19), whereas the seals associated with posttransform reservoirs are generally shale.

Exploration

At the time of the 2009 assessment, the Coastal Plain and Offshore Assessment Unit contained 21 oil fields and 19 gas fields exceeding the minimum size of 1 million barrels of oil equivalent (MMBOE). The Gulf of Guinea Province is considered immature with respect to its limited exploration activity. The largest grown oil field is the Jubilee field (fig. 3) with about 2,971 million barrels of oil (MMBO), and the largest grown gas field (Foxtrot, fig. 3) is about 1.01 trillion cubic feet.

Producing fields (IHS Energy, 2008) provide evidence for two inferences: the existence of an active petroleum system containing Cretaceous source rocks that have produced hydrocarbons most likely since the Late Cretaceous, and the migration of hydrocarbons into Cretaceous reservoirs.

Geologic Model

The geologic model developed for the assessment of conventional oil and gas in the Gulf of Guinea Province and the Coastal Plain and Offshore AU is as follows:

1. Hydrocarbons were generated from Early to Late Cretaceous marine source rocks. The primary source rocks are Turonian in age and contain Type II kerogen. Other source rocks are Albian and Cenomanian marine shale with Type II and II-III oil-prone kerogen and Type III terrestrial kerogen. For the Turonian and Coniacian source rocks, hydrocarbon generation possibly started in the early Tertiary and continues to the present. Hydrocarbon generation started in the Late Cretaceous for the Albian to Cenomanian source rocks and continues to the present.

2. Hydrocarbons migrated into Cretaceous turbidite-sandstone units, including syntransform and posttransform ponded turbidites, turbidite channels, and slope fans in basins between the major fracture zones. Potential hydrocarbon accumulations may be found in limestone units. Hydrocarbons migrated either directly from adjacent source rocks or upward along faults from deeper sources.

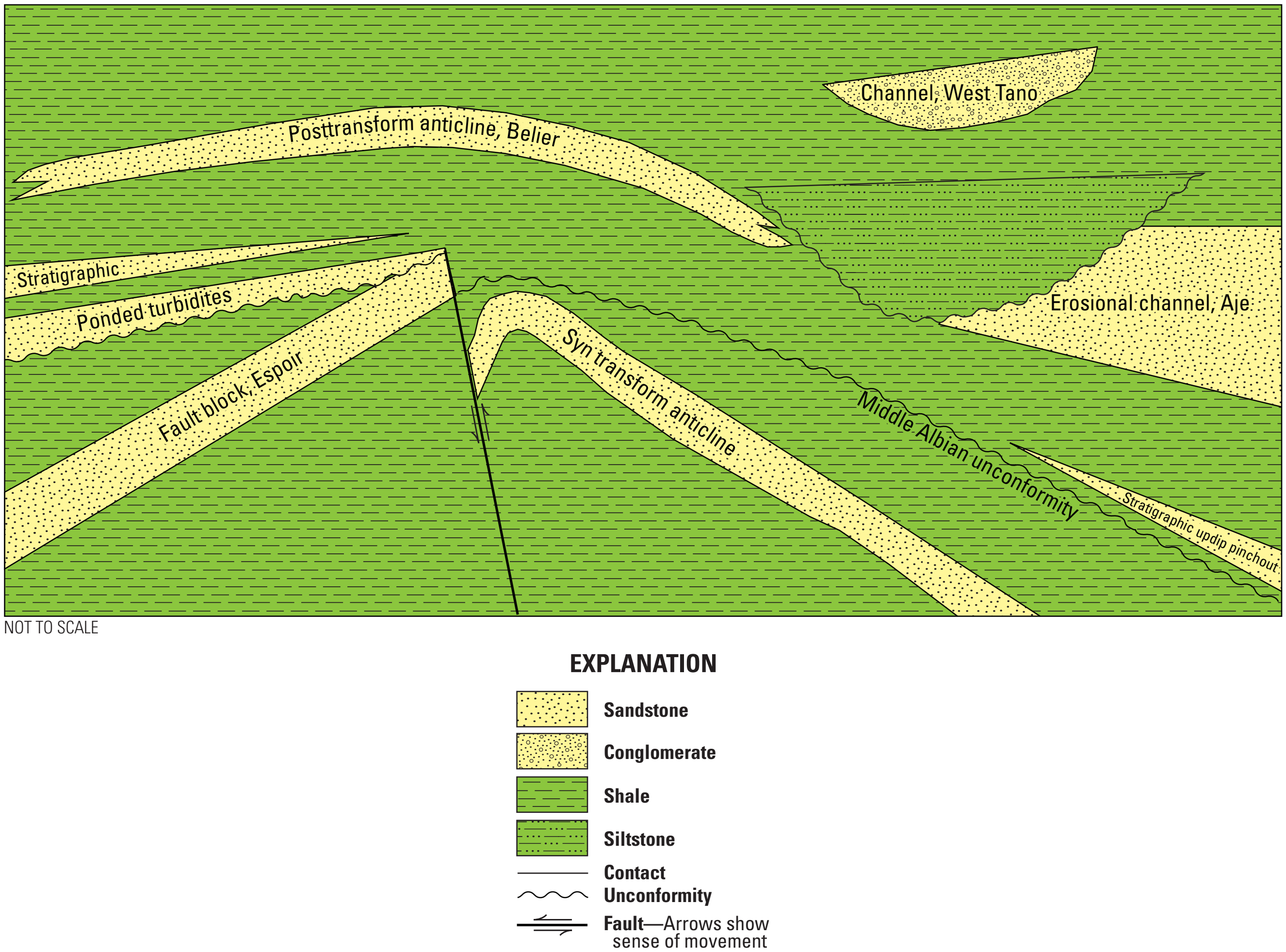


Figure 20. Schematic cross section showing common trap types and oil- and gas-field analogs (fig. 3) in Gulf of Guinea Province. Many of the trap types are present only in deep-water parts of the province and have not been tested. Modified from MacGregor and others (2003). Not to scale.

3. The traps include pretransform traps related to fault blocks, syntransform structural and stratigraphic traps, and posttransform stratigraphic traps.
4. Reservoirs seals are marine shale and shale-filled channels with minor fault-related seals.
5. An events chart (fig. 17) for the Cretaceous Composite TPS and the Coastal Plain and Offshore AU summarizes the age of the source, seal, and reservoir rocks and the timing of trap development and generation and migration of hydrocarbons.

Resource Summary

The Coastal Plain and Offshore Assessment Unit contains mostly Cretaceous sand reservoirs associated with pretransform fault blocks and syntransform and posttransform ponded turbidite sands and channels, and slope fans in basins between the major fracture zones. Stratigraphic traps associated with slope truncations along the present-day shelf and paleoshelf edge may also be present. The boundary of this assessment unit was defined to match that of the Gulf of Guinea Province; the northern boundary of the assessment unit is defined as the northern limit of the Cretaceous rocks, and the southern boundary is drawn at a water depth of 4,000 meters. Although potential reservoirs in this assessment unit could exist in the shallow-water part, most of the potential resource is expected to be in the deep-water part of the province.

Using a geology-based assessment, the U.S. Geological Survey estimated mean volumes of undiscovered, technically recoverable conventional oil and gas resources for the Coastal Plain and Offshore Assessment Unit in the Gulf of Guinea Province (table 1). The mean volumes are estimated at 4,071 million barrels of oil, 34,461 billion cubic feet of gas, and 1,145 million barrels of natural gas liquids. The estimated mean size of the largest oil field that is expected to be discovered is 1,737 million barrels of oil, and the estimated mean size of the expected largest gas field is 10,409 billion cubic feet of gas. For this assessment, a minimum undiscovered field size of 1 million barrels of oil equivalent was used. No attempt was made to estimate economically recoverable reserves.

Table 1. Assessment results for undiscovered, technically recoverable oil, gas, and natural gas liquids, Gulf of Guinea Province and the Coastal Plain and Offshore Assessment Unit, Africa.

[Largest expected mean field size in million barrels of oil and billion cubic feet of gas. MMBO, million barrels of oil; BCFG, billion cubic feet of gas; MMBNGL, million barrels of natural gas liquids. Results shown are fully risked estimates. For gas accumulations, all liquids are included as natural gas liquids (NGL). Undiscovered gas resources are the sum of nonassociated and associated gas. F95 represents a 95-percent chance of at least the amount tabulated; other fractiles are defined similarly. AU, assessment unit; AU probability is the chance of at least one accumulation of minimum size within the AU. TPS, total petroleum system. Gray shading indicates not applicable]

Total Petroleum Systems (TPS) and Assessment Units (AU)	Field type	Largest expected mean field size	Total undiscovered resources											
			Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
West African Coastal Province—Cretaceous Composite TPS														
Coastal Plain and Offshore AU	***Oil***	1,737	563	2,966	11,409	4,071	1,347	7,224	29,054	10,126	68	365	1,466	513
	Gas	10,409					3,382	17,704	68,094	24,335	87	457	1,782	632
Total Conventional Resources			563	**2,966**	**11,409**	**4,071**	**4,729**	**24,928**	**97,148**	**34,461**	**155**	**822**	**3,248**	**1,145**

For Additional Information

Assessment results are available at the USGS Central Energy Resources Science Center website: http://energy.usgs.gov/OilGas/ or contact Michael E. Brownfield, the assessing geologist (*mbrownfield@usgs.gov*).

Acknowledgments

The author wishes to thank Mary-Margaret Coates, Jennifer Eoff, Christopher Schenk, and David Scott for their suggestions, comments, and editorial reviews, which greatly improved the manuscript. The author thanks Wayne Husband for his numerous hours drafting many of the figures used in this manuscript, and Chris Anderson, who supplied the Geographic Information System files for this assessment.

References

Binks, R.M., and Fairhead, J.D., 1992, A plate tectonic setting for Mesozoic rifts of west and central Africa: Tectonophysics, v. 213, p. 141–151.

Blarez, E., and Mascle, Jean, 1988, Shallow structures and evolution of the Ivory Coast and Ghana transform margin: Marine and Petroleum Geology, v. 5, p. 54–64.

Brownfield, M.E., and Charpentier, R.R., 2006a, Geology and total petroleum systems of the Gulf of Guinea Province of West Africa: U.S. Geological Survey Bulletin 2207–C, 32 p.

Brownfield, M.E., and Charpentier, R.R., 2006b, Geology and total petroleum systems of the West-Central Coastal Province (7203), West Africa: U.S. Geological Survey Bulletin 2207–B, 52 p.

Chierici, M.A., 1996, Stratigraphy, palaeoenvironments and geological evolution of the Ivory Coast–Ghana basin, *in* Jardiné, S., de Klasz, I., and Debenay, J.-P., eds., Géologie de l'Afrique et de l'Atlantique Sud, 12 e Colloque de Micropaléontologie Africaine, 2 e Colloque de Stratigraphie et Paléogéographie de l'Atlantique Sud, Angers, France, 1994, Recueil des Communications: Pau, Elf Aquitaine, Memoire 16, p. 293–303.

Clifford, A.C., 1986, African oil—Past, present, and future, *in* Halbouty, M.T., ed., Future petroleum provinces of the world: Wallace E. Pratt Memorial Conference, Phoenix, December 1984, Proceedings: American Association of Petroleum Geologists Memoir 40, p. 339–372.

Dumestre, M.A., 1985, Northern Gulf of Guinea shows promise: Oil and Gas Journal, v. 83, no. 18, p. 154–165.

Elvsborg, A., and Dalode, J., 1985, Benin hydrocarbon potential looks promising: Oil and Gas Journal, v. 82, p. 126–131.

Emery, K.O., and Uchupi, E., 1984, Geology of the Atlantic Ocean: New York, Springer Verlag, 1,050 p.

Genik, G.J., 1993, Petroleum geology of the Cretaceous-Tertiary rift basins in Niger, Chad, and Central African Republic: American Association of Petroleum Geologists Bulletin, v. 73, no. 8, p. 153–168.

Grillot, L.R., Anderton, P.W., Haselton, T.M., and Demergne, J.F., 1991, Three-dimensional seismic interpretation, Espoir Field area, offshore Ivory Coast, *in* Brown, A.R., ed., 3-D seismic interpretation: American Association of Petroleum Geologists Memoir 42, p. 214–217.

Guiraud, Rene, and Maurin, Jean-Christophe, 1992, Early Cretaceous rifts of western and central Africa—An overview: Tectonophysics, v. 213, p. 153–168.

Haack, R.C., Sundararaman, P., Diedjomahor, J.O., Xiao, H., Gant, N.J., May, E.D., and Kelsch, K., 2000, Niger Delta petroleum systems, Nigeria, *in* Mello, M.R., and Katz, B.J., eds., Petroleum systems of South Atlantic margins: American Association of Petroleum Geologists Memoir 73, p. 213–231.

IHS Energy, 2008, International petroleum exploration and production database [current through December 2008]: available from IHS Energy, 15 Inverness Way East, Englewood, Colo. 80112, U.S.A.

Kesse, G.O., 1986, Oil and gas possibilities on- and offshore Ghana, *in* Halbouty, M.T., ed., Future petroleum provinces of the world, Wallace E. Pratt Memorial Conference, Phoenix, December 1984, Proceedings: AAPG Memoir 40, p. 427–444.

Kjemperud, A., Agbesinyale, W., Agdestein, T., Gustafsson, C., and Yükler, A., 1992, Tectono-stratigraphic history of the Keta Basin, Ghana with emphasis on late erosional episodes, *in* Curnelle, R., ed., Géologie Africaine–1er colloques de stratigraphie et de paléógéographie des basins sédimentaires oust–Africains, 2 e Colloque Africain de Micropaleontologie, Libreville, Gabon, May 6–8, 1991: Elf Aquitaine, Mémoire 13, p. 55–69.

Klett, T.R., Ahlbrandt, T.A., Schmoker, J.W., and Dolton, G.L., 1997, Ranking of the world's oil and gas provinces by known petroleum volumes: U.S. Geological Survey Open-File Report 97–463, CD–ROM.

Kulke, H., 1995, Côte d'Ivoire (former Ivory Coast), Ghana and Togo, *in* Kulke, H., ed., Regional petroleum geology of the world, part II, Africa, America, Australia, and Antarctica: Berlin, Gebrüder Borntraeger, p. 129–135.

Lambiase, J.J., 1989, The framework of African rifting during the Phanerozoic: Journal of African Earth Science, v. 8, no. 2/3/4, p. 183–190.

Lehner, Peter, and De Ritter, P.A.C., 1977, Structural history of Atlantic margin of Africa: AAPG Bulletin, v. 61, no. 7, p. 961–981.

MacGregor, D.S., Robinson, J., and Spear, G., 2003, Play fairways of the Gulf of Guinea transform margin, *in* Arthur, T.J., MacGregor, D.S., and Cameron, N.R., eds., Petroleum geology of Africa—New themes and developing technologies: Geological Society, London, Special Publications, v. 207, p. 131–150. doi10.1144/GSL.SP.2003.207.7.

Mascle, Jean, Blarez, Emmanuel, and Marinho, Marta, 1988, The shallow structures of the Guinea and Ivory Coast–Ghana transform margins—Their bearing on the equatorial Atlantic Mesozoic evolution: Tectonophysics, v. 155, p. 193–209.

McHargue, T.R., 1990, Stratigraphic development of proto-south Atlantic rifting in Cabinda, Angola—A petroliferous lake basin, *in* Katz, B.J., ed., Lacustrine basin exploration case studies and modern analogs: American Association of Petroleum Geologists Memoir 50, p. 307–326.

Persits, F.M., Ahlbrandt, T.S., Tuttle, M.L., Charpentier, R.R., Brownfield, M.E., and Takahashi, K.I., 2002, Map showing geology, oil and gas fields, and geologic provinces of Africa: U.S. Geological Survey Open-File Report 97–470A, version 2.0, CD–ROM.

Teisserenc, P., and Villemin, J., 1990, Sedimentary basin of Gabon—Geology and oil systems, *in* Edwards, J.D., and Santogrossi, P.A., eds., Divergent/passive margin basins: American Association of Petroleum Geologists Memoir 48, p. 117–199.

Tissot, B., Demaison, G., Masson, P., Delteil, J.R., and Combaz, A., 1980, Paleoenvironment and petroleum potential of middle Cretaceous black shales in Atlantic basins: American Association of Petroleum Geologists Bulletin, v. 64, no. 12, p. 2051–2063.

Tucker, J.W., 1992, Aspects of the Tano Basin stratigraphy revealed by recent drilling in Ghana, *in* Curnelle, R., ed., Géologie Africaine–1er colloques de stratigraphie et de paléógéographie des basins sédimentaires oust–Africains, 2e Colloque Africain de Micropaleontologie, Libreville, Gabon, May 6–8, 1991: Elf Aquitaine, Mémoire 13, p. 153–159.

U.S. Geological Survey Geologic Names Committee, 2010, Divisions of geologic time: U.S. Geological Survey Fact Sheet 2010–3059, 2 p.

U.S. Geological Survey World Conventional Resources Assessment Team, 2012, An estimate of undiscovered conventional oil and gas resources of the world, 2012: U.S. Geological Survey Fact Sheet 2012–3042, 6 p. Available at http://pubs.usgs.gov/fs/2012/3042/.

U.S. Geological Survey World Energy Assessment Team, 2000, U.S. Geological Survey World Petroleum Assessment 2000—Description and results: U.S. Geological Survey Digital Data Series DDS-60, four CD–ROMs.

Ziegler, D.G., 1988, Early Mesozoic plate reorganization, *in* Ziegler, D.G., ed., Evolution of the Arctic–North Atlantic and the Western Tethys: American Association of Petroleum Geologists Memoir 43, p. 43–61.

Click here to return to
Volume Title Page